Mitigating the detrimental effects of hot and dry summers on the south-eastern Australian dairy feed-base

By

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DECLARATIONS

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ABSTRACT

This thesis investigated strategies for mitigating detrimental effects of hot and dry summers (i.e. supraoptimal temperatures and soil water deficit stress) on home-grown feed production in south-eastern Australian dairying regions. Strategies included incorporating alternative species into the feed-base and modifying aspects of feed-base management. Field research was conducted in north-west Tasmania, where summer conditions are forecast to become hotter during the 21st century, challenging the existing perennial ryegrass (*Lolium perenne* L.) feed-base.

A glasshouse study (Chapter 3) identified summer-active temperate perennial forages more tolerant than perennial ryegrass of the combined stress of supraoptimal temperatures and water deficit. These species were examined as they are known to possess key attributes underpinning perennial ryegrass' popularity (i.e. they are perennial, grazeable, and of high nutritive value). Species exhibiting greater tolerance than perennial ryegrass included chicory (*Cichorium intybus* L.), and to a lesser extent lucerne (*Medicago sativa* L.), plantain (*Plantago lanceolata* L.), and tall fescue (*Festuca arundinacea* Schreb.). Tolerance did not pertain to growth occurring when exposed to the combination of stresses, but was a result of these plants capacity to survive and resume growth when more favourable conditions returned.

An accompanying field experiment (Chapter 6) tested the potential of chicory and tall fescue to increase summer-autumn growth beyond that achievable by perennial ryegrass in north-west Tasmania. Under both irrigated and rain-fed conditions, chicory did not increase summer-autumn growth beyond that achieved by perennial ryegrass. In contrast, irrigated tall fescue achieved a similar total yield to comparably managed perennial ryegrass over a 15-month period, and in the second of two growing seasons, 10% greater summer-autumn yields. The potential role of tall fescue in north-west Tasmania was further demonstrated by the species high marginal irrigation water-use index (1.6-2.7 t DM/ML). Field research showed rain-fed chicory and second year tall fescue swards experienced less extreme crown (plant-soil interface) temperatures than perennial ryegrass (Chapter 4). This feature may contribute to their superior growth in hotter summer environments than north-west Tasmania.

Field research confirmed the crown temperatures of these species can be manipulated by both stubble height (height of stubble above the soil surface post-defoliation) and irrigation

management. Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) elevated the upper distribution of crown temperature (75th and 90th percentiles) in subsequent regrowth cycles (Chapter 4). In the second of two summers, defoliating to shorter stubble heights increased the 90th percentile of crown temperature by an average of 4.2°C for perennial ryegrass, 3.6°C for tall fescue, and 1.8°C for chicory. Differences in crown temperatures may be partly attributed to the canopy base being less shaded when defoliated to shorter stubble heights (i.e. swards having lower leaf area indices). Despite experiencing these higher summer crown temperatures, each species achieved greater summer-autumn yields when defoliated to shorter stubble heights (Chapter 6). This is explained by north-west Tasmania's cool temperate climate, limiting the extent and/or duration of supraoptimal crown temperatures.

Irrigation mitigated detrimental effects of supraoptimal temperature stress on growth and survival of all species examined in the glasshouse study (Chapter 3). Field research tested the role of irrigation frequency in mitigating the detrimental effects of supraoptimal temperature stress on perennial ryegrass pastures (Chapter 5). Addressing this research question necessitated the development of a novel outdoor warming system to reliably simulate heat wave conditions. The developed outdoor warming system was successfully deployed, with results showing irrigating at higher frequencies suppressed elevation of perennial ryegrass crown temperature under heaters. The median crown temperature differential between heated and unheated plots equalled 5.5°C, 6.5°C, and 7.0°C for swards irrigated every 2, 5, and 10 days respectively. Because soil water deficits never developed to an extent where transpiration was unduly constrained, irrigating more frequently did not mitigate the detrimental effects of applied heating on growth of perennial ryegrass.

These experiments have: (i) identified summer-active temperate perennial forages more tolerant than perennial ryegrass of the combined stress of supraoptimal temperatures and water deficit; (ii) found, in north-west Tasmania, irrigated tall fescue summer-autumn growth can exceed that achieved by comparably managed perennial ryegrass; (iii) shown, defoliating to higher stubble heights and irrigating more frequently maintains cooler crown temperatures; and (iv) developed a novel outdoor warming system for use in evaluating heat wave mitigation strategies. Identification of species more tolerant of hot and dry conditions, and management strategies that limit crown temperature elevation, are important steps in future-proofing north-west Tasmanian dairy farming systems against a warming climate. When interpreting results from field experiments, the influence of environment as a

component of the genotype by environment by management interaction should not be ignored. In south-eastern Australian dairying regions warmer than north-west Tasmania, the application of management practices that maintain cooler crown temperatures may benefit temperate pasture production. This requires confirmation, with future research also required to evaluate the potential role of these management practices at a whole farm system level.

STATEMENT OF CO-AUTHORSHIP

This PhD thesis has four experimental chapters. Two chapters have been published (Chapters 3 and 6) and one has been accepted for publication (Chapter 4).

The following people and institutions contributed to the publication of work undertaken as part of this thesis.

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Published in Journal of Crop and Pasture Science

Candidate was the primary author, contributing 75% to the research project and subsequent paper. The candidate designed and managed the experiment, planned and interpreted data analysis, and wrote the manuscript.

Author 1 and **Author 3** guided experimental design and management, advised data analysis and revised the manuscript. **Author 2** advised data analysis and revised the manuscript. **Author 4** guided experimental design and revised the manuscript. **Author 5** and **Author 6** guided experimental design. **Author 7** guided experimental

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Chapter 4, Effect of stubble height management on crown temperature of perennial ryegrass, tall fescue and chicory

Accepted for publication in Journal of Crop and Pasture Science

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Chapter 5, Imposing summer heat wave conditions in pasture using small-plot outdoor warming systems: A review and recommendations

To be submitted to Journal of Agricultural and Forest Meteorology

Candidate was the primary author, contributing 70% to the research project and subsequent paper. The candidate reviewed the literature, conceived the novel outdoor warming control system, designed and managed the experiment, planned and interpreted data analysis, and wrote the manuscript.

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Chapter 6, Effect of stubble height and irrigation management on the growth, botanical composition and persistence of perennial ryegrass, tall fescue, and chicory swards in cool-temperate Tasmania

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Author 1 and **Author 2** guided experimental design and management, advised data analysis planning and revised the manuscript. **Author 3** and **Author 4** guided experimental design and revised the manuscript. **Author 5** and **Author 6** guided experimental design. **Author 7** guided experimental design, assisted data analysis planning, analysed data and revised the manuscript.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published (or submitted) peer-reviewed manuscripts contributing to this thesis.

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OTHER PUBLICATIONS AND ACHIEVEMENTS ARISING DURING CANDIDATURE

PEER-REVIEWED SCIENCE PUBLICATIONS

Rawnsley RP, Langworthy AD, Pembleton KG, Turner LR, Corkrey R, Donaghy DJ (2014) Quantifying the interactions between grazing interval, grazing intensity, and nitrogen on the yield and growth rate of dryland and irrigated perennial ryegrass. *Crop & Pasture Science* **65**, 735-746.

SCIENCE CONFERENCE ORAL PRESENTATIONS

Langworthy AD, Rawnsley RP, Pembleton KG, Freeman MJ, Harrison MT, Lane PA, Henry DA, Corkrey R (2016) Optimising summer defoliation residual height to maximise perennial ryegrass (*Lolium perenne* L.), chicory (*Cichorium intybus* L.), and tall fescue (*Festuca arundinacea* Schreb.) persistence and performance under different irrigation levels, In 'Proceedings of the 7th Australasian Dairy Science Symposium. Sydney, New South Wales, Australia'. pp. 32 (University of Sydney: Sydney, New South Wales, Australia).

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POSTER PRESENTATIONS

Langworthy AD (2015) Chicory helps dairy farmers beat the heat during summer drought in southeast Australia, In. 'Proceedings of the University of Tasmania's 9th Annual Graduate Research Conference. Hobart, Tasmania, Australia'. (University of Tasmania: Tasmania, Australia).

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2014 Australian Sustainable Agriculture 'Operation Only' Scholarship

2013 Australian Postgraduate Award

2013 Cuthbertson Elite Tasmanian Graduate Research Scholarship

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ABBREVIATIONS

List of abbreviations used in main body text.

a.i.	Active Ingredient
a.m.s.l	Above Mean Sea Level
AC	Alternating Current
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
AU$	Australian Dollar
c	Control Offset
Cat5e	Category 5e
cmol	Centimole
cv.	Cultivar
D_n	Defoliation
DAS	Days After Sowing
DM	Dry Matter
dS	Decisiemens
ET	Evapotranspiration
exp	Exponential
FC	Field Capacity (10 kPa Extraction Pressure)
F_v/F_m	Chlorophyll Fluorescence Ratio
g	Gain Value
GS	Growing Season
h	Hour
H_n	Harvest
HSS	Hours Since Start
IR	Infrared
LAI	Leaf Area Index
ME	Metabolisable Energy
min	Minute
MIWUI	Marginal Irrigation Water-Use Index
MJ	Megajoule
NDF	Neutral-Detergent Fibre
NSC	Non-Structural Carbohydrate
NW	North-West
OTC	Open-Top Chamber
PAR	Photosynthetically Active Radiation
PAWC	Plant Available Water Capacity
PCBs	Printed Circuit Boards

P_n	Persistence Assessment
PSII	Photosystem II
RCB	Randomised Complete Block
RC_n	Regrowth Cycle
RH	Relative Humidity
RuBisCO	Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase
s	Second
SE	South-Eastern
SR	Solar Radiation
SSP	Single Super Phosphate
SWC	Soil Water Content
t	Offset Temperature
T_a	Ambient Temperature
T_c	Canopy Temperature
T_s	Soil Temperature
T_t	Tiller Temperature
ΔT	Temperature Differential
TRIAC	Triode for Alternating Current
VPD	Vapour Pressure Deficit
w/w	Weight Per Weight
WP	Wilting Point (1500 kPa Extraction Pressure)
Z_r	Rooting Depth
θ_v	Volumetric Water Content
μ	Mean
μ_h	Mean Heated Plot Temperature
μ_{uh}	Mean Unheated Reference Plot Temperature

Chapter 1**: General introduction**

1.1 INTRODUCTION

Dairying is Australia's third largest rural industry, with >85% of milk production occurring in south-eastern (SE) regions (Kempton 2015; Dairy Australia 2017). Grazed pasture is the cheapest feed source and attaining high levels of home-grown feed production underpins business success (Savage and Lewis 2005; Chapman *et al.* 2008a). Perennial ryegrass (*Lolium perenne* L.) is the main sown pasture species in SE Australian dairying regions (Chapman *et al.* 2006; Jacobs and Woodward 2010), averaging 60-70% of a dairy cow's ration (Chapman *et al.* 2008a). Reasons for the widespread usage of perennial ryegrass include its ease of establishment (Reed *et al.* 2008), high annual yield potential (>20 t dry matter/hectare if irrigated), high nutritive value (Garcia and Fulkerson 2005), grazing tolerance (Wilkins 1991), and responsiveness to nitrogen fertiliser (Pembleton *et al.* 2013).

Perennial ryegrass has a disadvantage of exhibiting strong seasonality in growth and nutritive value (Jacobs *et al.* 1999; Chapman *et al.* 2008a). Cumulative summer yields (January-February) achieved by rain-fed perennial ryegrass pasture can be as low as 5-10% of annual production (Özkan *et al.* 2015). This can be explained by perennial ryegrass's sensitivity to the hot and dry summer conditions that frequently occur in many SE Australian dairying regions (Mitchell 1956; Norris 1982; Rawnsley *et al.* 2007a). Summer conditions are projected to become even more challenging for perennial ryegrass-based pasture production in SE Australia (Harrison *et al.* 2016; Harrison *et al.* 2017).

The sensitivity of perennial ryegrass growth to dry conditions (i.e. soil water deficit) largely results from the species shallow root system (Garwood and Sinclair 1979; Crush *et al.* 2005). Even when irrigated, the growth and persistence of perennial ryegrass remains challenged by above optimal (supraoptimal) ambient temperatures (≥30˚C) (Arcioni *et al.* 1985; Neal *et al.* 2009). Supraoptimal temperature stress is particularly problematic for rain-fed pastures experiencing soil water deficit, as the combination of stresses have a greater negative effect on plant growth and survival than either individual stress (i.e. they act synergistically) (Jiang and Huang 2000, 2001b). This is because soil water deficits constrain transpiration (Feldhake *et al.* 1984; Temple and Benoit 1988), limiting the ability of plants to avoid detrimental effects of supraoptimal temperature stress. Transpiration enables plants to avoid supraoptimal temperature stress, as transpiration can depress forage canopy temperatures by more than 7˚C below the ambient temperature (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004; Richardson 2004).

This thesis investigates strategies for mitigating detrimental effects of hot and dry summer conditions on home-grown feed production in SE Australian dairying regions. Investigated mitigation strategies include: (i) incorporating alternative species into the feed-base; (ii) and modifying aspects of feed-base management, including stubble height (height of stubble above the soil surface post-defoliation) and irrigation frequency.

1.2 THESIS OUTLINE

This "thesis by publication" follows University of Tasmania guidelines. It includes a literature review (Chapter 2), four experimental chapters (Chapters 3 to 6), and concludes with a general discussion (Chapter 7). Experimental chapters are formatted as journal manuscripts, with further detail provided in the *Statement of Co-Authorship* (vi to viii). The *Journal of Crop and Pasture Science* referencing style is adopted throughout this thesis for document uniformity.

An initial literature review (Chapter 2) highlights the challenges of hot and dry summer conditions for home-grown feed production in SE Australian dairying regions. Potential mitigation strategies are the focus of this review and relate to both management and incorporating alternative species into the feed-base.

The literature review (Chapter 2) identified species having potential to increase summer home-grown feed production in SE Australian dairy regions. A glasshouse study reported in Chapter 3 tested the hypothesis that some of these species are more tolerant of supraoptimal temperature stress than perennial ryegrass. Supraoptimal temperature stress was imposed under both irrigated and non-irrigated conditions.

Research reported in all subsequent experimental chapters (Chapters 4 to 6) was conducted under field conditions in north-west (NW) Tasmania, where summer conditions are forecast by 2040 to become hotter and challenge the existing perennial ryegrass dominated feed-base (White *et al.* 2010; Harrison *et al.* 2016; Harrison *et al.* 2017). Many reported findings are applicable to other SE Australian dairying regions, where hot and dry summer conditions already constrain growth of perennial ryegrass (Rawnsley *et al.* 2007a).

The literature review (Chapter 2) identified the increased insolation following herbage removal via grazing or mechanical defoliation can result in the elevation of crown (plant-

soil interface) temperatures. This can have detrimental effects on pasture species experiencing supraoptimal temperature stress. Research, presented in Chapter 4, tested the hypothesis defoliating to shorter stubble heights would elevate the upper distribution of crown temperatures (75th and 90th percentiles) experienced by three pasture species. Examined species included perennial ryegrass, tall fescue and chicory. Tall fescue and chicory were included as two of the most promising species identified from the glasshouse experiment (Chapter 3).

The glasshouse study (Chapter 3) showed irrigation mitigated detrimental effects of supraoptimal temperature stress on perennial ryegrass growth and survival. As it is often impractical to irrigate on a daily basis depending on irrigation system (as practiced in the glasshouse study), research, reported in Chapter 5, tested the hypothesis irrigating more frequently reduces detrimental effects of heat waves on perennial ryegrass growth and short-term persistence. This research required the development of an outdoor warming system that could reliably simulate heat wave conditions. Chapter 5 documents the development and appraisal of this system when applied in field conditions.

To conclude the experimental section of this thesis, Chapter 6 reports results from a field experiment investigating the combined effect of applying the reported mitigation strategies on summer-autumn pasture production. Species examined included perennial ryegrass, tall fescue, and chicory. The main aim of this research was to further elucidate the effect of stubble height management on the growth of these species under either contrasting irrigation schedules or rain-fed conditions. Research, reported in Chapter 6, tested the hypothesis that in NW Tasmania, tall fescue and chicory can be grown to increase summer-autumn growth beyond that achievable by perennial ryegrass.

This thesis concludes with a general discussion (Chapter 7) reporting key findings and conclusions determined by the research presented in this thesis (Chapters 3 to 6) and highlights subsequent research avenues.

Chapter 2**: Literature review**

2.1 OVERVIEW OF CHAPTER 2

This literature review highlights the challenges of hot and dry summer conditions for the perennial ryegrass (*Lolium perenne* L.)-dominated feed-base in south-eastern Australian dairying regions. Potential strategies for mitigating detrimental effects from these abiotic stresses on summer home-grown feed supply are reviewed.

2.2 SCOPE OF REVIEW

Hot and dry summer conditions challenge home-grown feed production in many south-eastern (SE) Australian dairying regions. This challenge frequently occurs because the dominant pasture species, perennial ryegrass (*Lolium perenne* L.), and to a lesser extent white clover (*Trifolium repens* L.), possess limited tolerance to these conditions. Potential strategies for mitigating detrimental effects of hot and dry summer conditions on SE Australian dairy farming systems are the focus of this review. Strategies relate to both management (e.g. destocking, fodder conservation, grazing, irrigation, and soil fertility) and the incorporation of alternative species into the feed-base. This review identifies summer-active temperate perennial forages with potential to increase summer home-grown feed production. There is need to quantify these species tolerance to above optimal (supraoptimal) temperature stress. Once the most tolerant species are identified, there is a requirement to study their individual responses to changes in summer grazing and irrigation management. Further investigation of how these aspects of management can improve summer growth of the existing perennial ryegrass-based feed-base is also required.

2.3 SOUTH-EASTERN AUSTRALIAN DAIRY PASTURES

Grazed pasture is the cheapest feed available for dairy cows in SE Australia (Figure 2.1) (Dillon *et al.* 2005; Chapman *et al.* 2008b). Annual pasture consumption [t dry matter (DM)/hectare (ha)] is therefore key to many dairy business's profitability (Savage and Lewis 2005; Van Bysterveldt 2005; Chapman *et al.* 2008a). Perennial ryegrass is the main pasture species sown in SE Australian dairy regions (Chapman *et al.* 2006; Jacobs and Woodward 2010), averaging 60-70% of a dairy cow's daily ration (Chapman *et al.* 2008a). Reasons for the widespread usage of perennial ryegrass include its ease of establishment (Reed *et al.* 2008), high annual yield potential (>20 t DM/ha if irrigated), high nutritive value (Garcia and Fulkerson 2005), grazing tolerance (Wilkins 1991), and responsiveness to nitrogen (N) (Pembleton *et al.* 2013).

Perennial ryegrass is often sown in a simple binary mixture with white clover (Rawnsley *et al.* 2013). Advantages of white clover include its grazing tolerance (Nichols *et al.* 2012), and high nutritive value. White clover herbage has a higher metabolisable energy (ME) and lower fibre content than perennial ryegrass (Ulyatt 1981). White clover is also beneficial in

provisioning swards with N, via biological N fixation (Broadbent *et al.* 1982; Ledgard and Steele 1992; Ledgard *et al.* 2001).

Perennial ryegrass-based swards have the disadvantage of exhibiting strong seasonality in growth and nutritive value (Jacobs *et al.* 1999; Chapman *et al.* 2008a). This challenges a dairy producer's ability to maximise annual pasture consumption, and therefore business profitability (Moran *et al.* 2000; Dairy Australia 2015). Under rain-fed conditions up to 60% of annual pasture production in SE Australia occurs during spring (Nie *et al.* 2004a), with periods such as mid-winter and summer characterised by low pasture growth rates (≤20 kg/ha.day) (Cullen *et al.* 2008). During these periods, fodder conserved from the spring surplus (hay or silage), purchased feeds, and/or irrigation are often used to maintain stocking rates (cows/ha) (Chapman and Kenny 2005; Özkan *et al.* 2015).

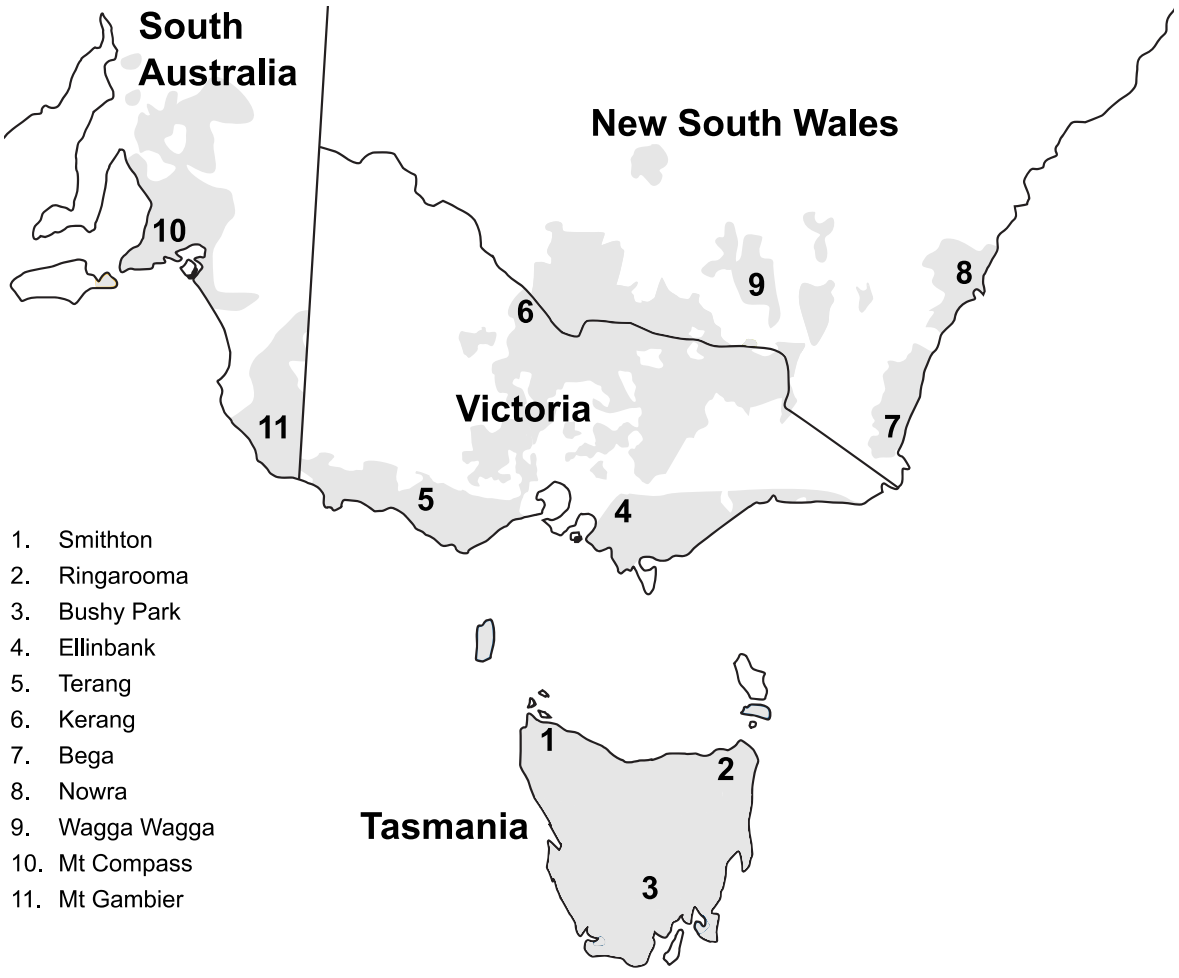

Figure 2.1 Map showing south-eastern Australian dairying regions (■) and the location of towns referenced in Figures 2.2 and 2.3. Adaptation of Figure provided courtesy of Dairy Australia Ltd.

2.3.1 Winter feed deficits

Winter feed deficits in SE Australian dairying regions primarily result from low (suboptimal) temperatures restricting growth (Rawnsley *et al.* 2007a). In the absence of soil water deficit, ambient temperatures (T_a) <6˚C inhibit temperate grass growth (Cooper and Tainton 1968). White clover growth is more sensitive to suboptimal temperatures stress than perennial ryegrass (Mitchell 1956; Kemp and Liu 1992). Other abiotic stresses constraining winter growth include frosts, restricted photosynthetically active radiation, and waterlogging on poorly drained soils (Rawnsley *et al.* 2007a). Winter feed deficits are not discussed further as they are not the focus of this review.

2.3.2 Summer feed deficits

2.3.2.1 Soil water deficits

In SE Australian dairying regions, cumulative summer yields (January-February) achieved by rain-fed pastures can be as low as 5-10% of annual production (Özkan *et al.* 2015). This can be partly explained by the low tolerance of perennial ryegrass and white clover to soil water deficit stress (Caradus 1990; Waller and Sale 2001; Chapman *et al.* 2009; Neal *et al.* 2009). Summer soil water deficits characterise rain-fed SE Australian dairy farming systems and result from evapotranspiration exceeding rainfall (Figure 2.2) (Rawnsley *et al.* 2007a; Rawnsley *et al.* 2013).

The sensitivity of perennial ryegrass and white clover to soil water deficit stress is largely explained by their shallow root systems (Garwood and Sinclair 1979; Guobin and Kemp 1992; Crush *et al.* 2005), with more than 60% of perennial ryegrass roots occurring in the top 0.2 m of the soil profile (Crush *et al.* 2005). White clover has an even less extensive root system (Evans 1978; Guobin and Kemp 1992; Lucero *et al.* 1999), with >80% of roots situated in the top 0.2 m of the soil profile (Bennett and Doss 1960; Caradus 1990). White clover's sensitivity to soil water deficit stress is also explained by the species limited capacity to control transpiration (Burch and Johns 1978).

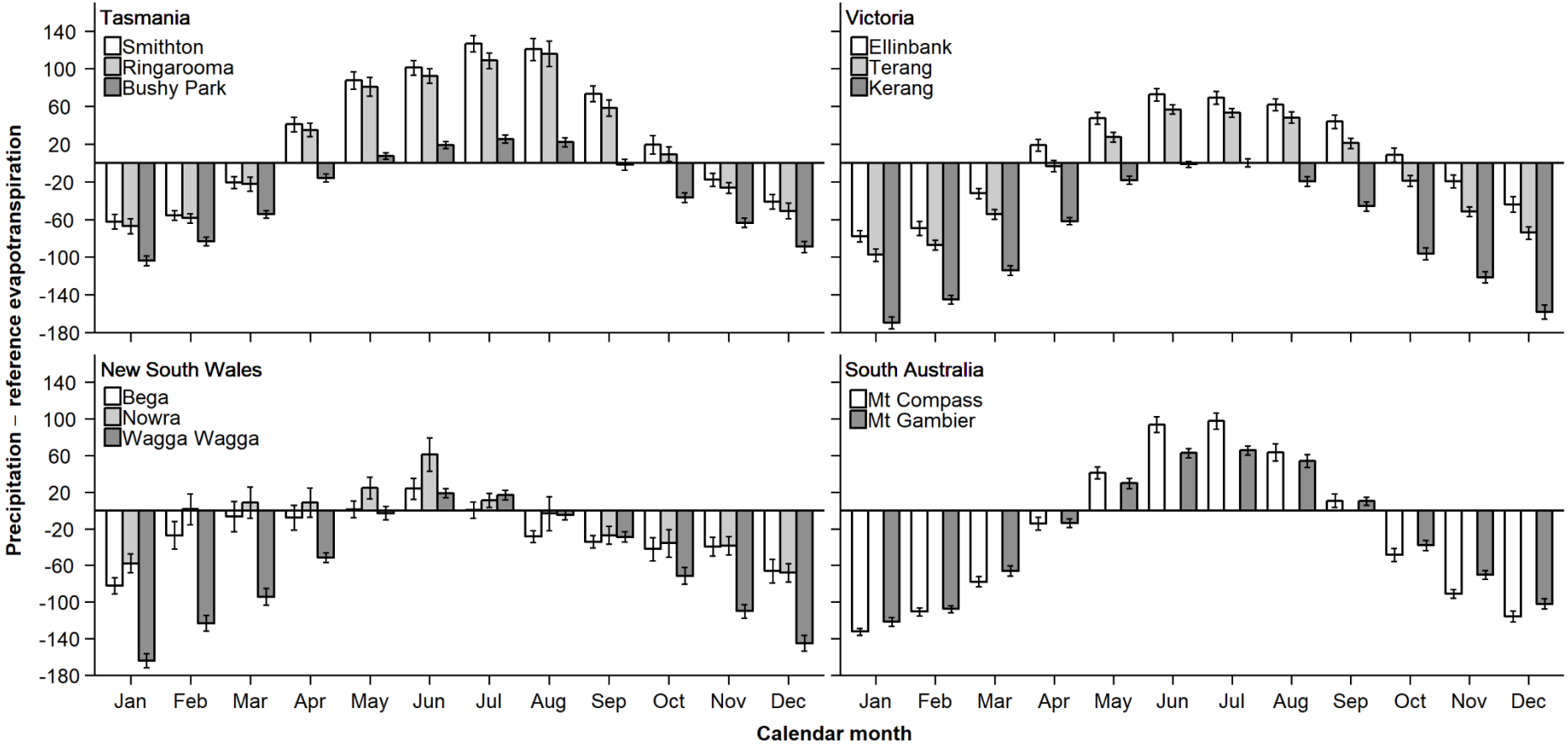

Figure 2.2 Long term (1976-2015) monthly precipitation (mm) – reference evapotranspiration (mm) values for south-eastern Australia dairying regions; location of towns shown in Figure 2.1. Values are means ± one standard error of the mean.

2.3.2.2 Supraoptimal temperature

Irrigation alleviates soil water deficits, with forage production consuming 30% of total agricultural water use in SE Australia (ABS 2015). Summer growth and persistence of irrigated perennial ryegrass and white clover swards remain challenged by supraoptimal temperatures (T_a ≥30˚C) (Figure 2.3) (Arcioni *et al.* 1985; Lawson *et al.* 1997; Neal *et al.* 2009). Supraoptimal temperature stress has become an increasing problem in SE Australia (Steffen *et al.* 2014), with two of the region's most severe heat waves in the last century having occurred since 2009 (BoM 2014).

Supraoptimal temperature stress is especially problematic for rain-fed pastures experiencing soil water deficit, as the combined stresses have a greater negative effect on plant growth and survival than either individual stress (i.e., they act synergistically) (Jiang and Huang 2000, 2001b). This is because soil water deficits constrain transpiration limiting the ability of plants to avoid the detrimental effects of supraoptimal temperature stress (Feldhake *et al.* 1984; Temple and Benoit 1988). Transpiration enables plants to avoid supraoptimal temperature stress, as transpiration can depress canopy temperature by more than 7˚C below T_a (i.e. transpirational cooling) (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004; Richardson 2004).

The reduction in growth of perennial ryegrass during hot summer conditions is explained by its relatively low optimum T_a of between 20˚C to 25˚C, depending on irradiance level (Mitchell 1956; Mitchell and Lucanus 1962; Silsbury 1969, 1971; Sasaki *et al.* 2001). When water is non-limiting, perennial ryegrass shoot growth is significantly reduced by T_a >29˚C, with all growth inhibited at 35˚C (Mitchell 1956). These temperatures commonly occur during summer in many SE Australian dairying regions (Figure 2.3). Detrimental effects of supraoptimal temperature stress on perennial ryegrass involve the imbalance of photochemical and biochemical processes, via reduced Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) activity. These processes result in toxic hydrogen peroxide accumulating in the tissues of supraoptimal temperature stressed plants (Soliman *et al.* 2012).

Perennial ryegrass genotypes more tolerant of supraoptimal temperatures have been postulated to contain a higher RuBisCO content, via thicker leaves. Soliman *et al.* (2012), proposed the greater leaf thickness of tetraploid relative to diploid genotypes to explain their superior capacity to tolerate supraoptimal temperatures. Genotypic differences in

supraoptimal temperature stress tolerance have also been related to the maintenance of non-structural carbohydrate (NSC) reserves. This conclusion was drawn from the survival and NSC content of an Italian genotype (cv. Vejo®) being superior to its' Northern European (cv. Lenta®) contemporary during a hot Italian summer (Arcioni *et al.* 1985). Arcioni *et al.* (1985) attributed these differences to the enhanced photosynthetic capacity of Vejo® at high T_a (25-30˚C). Gains in summer production have been attained from incorporating Spanish germplasm into commercial cultivars (Waller 2008; Matthew *et al.* 2012), which further demonstrates the value of perennial ryegrass genotypes from warmer and drier climates than Northern Europe. Despite the widespread use of tetraploid cultivars containing Spanish germplasm (e.g. Base®, Banquet II®, Bealey®), supraoptimal temperatures are recognised to still constrain perennial ryegrass growth in SE Australian dairying regions (Rawnsley *et al.* 2007a).

In contrast to perennial ryegrass, the response of white clover to hot summer conditions is less researched. White clover shoot growth has a higher optimum T_a than perennial ryegrass (24˚C vs. 20˚C) (Mitchell 1956). This is confirmed by observations of white clover plants yielding similarly when maintained under day/night (14/10 h) temperature regimes of 32/24˚C and 26/15˚C (Mannetje and Pritchard 1974). Subsequently, it is unsurprising white clover has greater summer yield potential than perennial ryegrass under irrigated conditions (Karsten and MacAdam 2001). Despite this, hot summer conditions reduce irrigated white clover growth in SE Australia (Nie *et al.* 2004b; Neal *et al.* 2009).

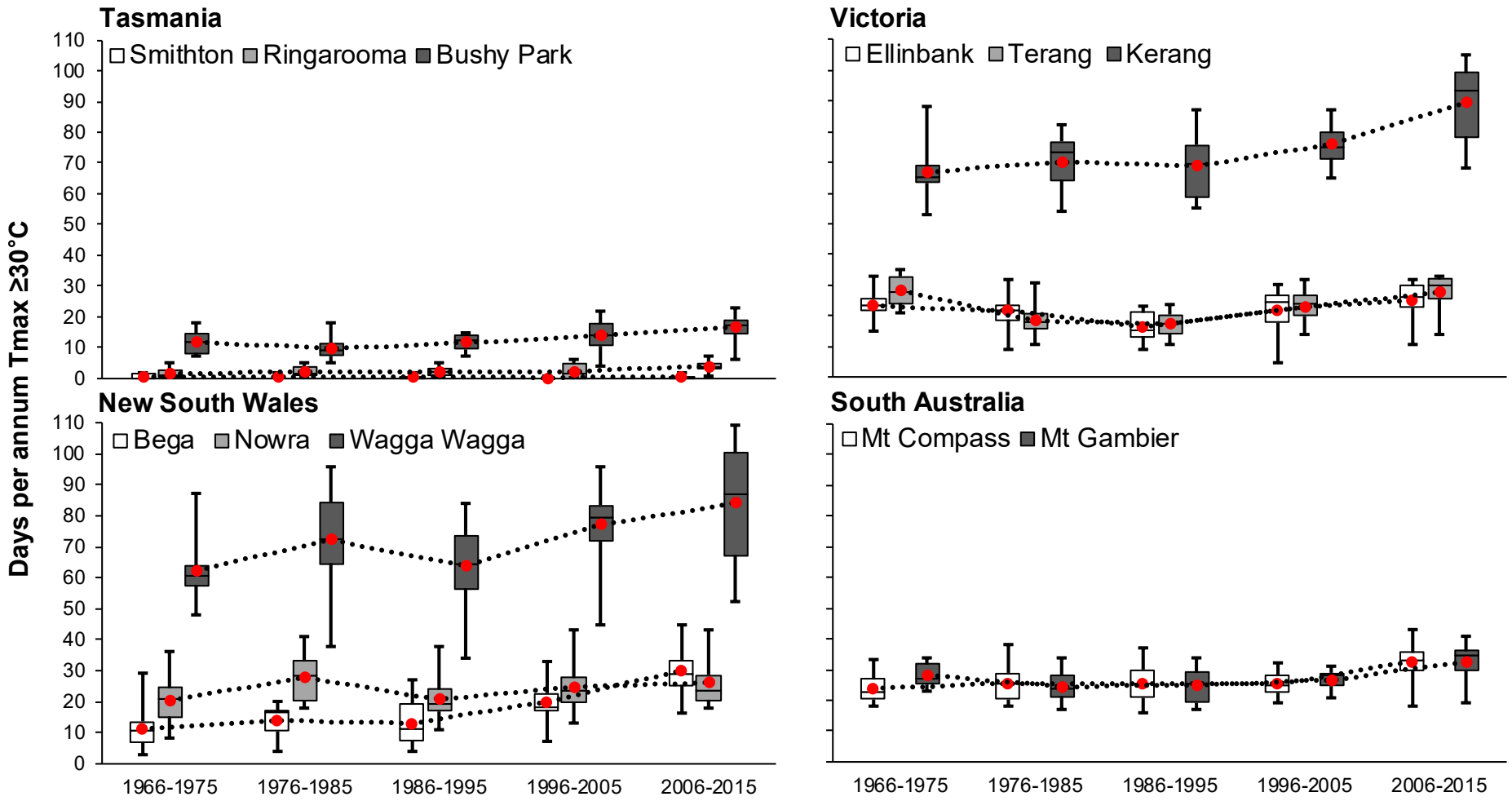

Figure 2.3 Box and whisker plots for the number of days per annum maximum daily ambient temperature (Tmax) ≥30˚C in south-eastern Australian dairying regions; location of towns shown in Figure 2.1. Lines represent median values (50th percentile), boxes represent 25th and 75th percentiles, and whiskers represent maximum and minimum values. Mean values (●) are also presented.

2.3.2.3 Future climate projections

In SE Australian dairying regions, summer conditions are projected to become even more challenging for perennial ryegrass-based pasture production during the 21st century (Harrison *et al.* 2016; Harrison *et al.* 2017). In general, the climate is forecast to become hotter and drier, with anticipated increases in the frequency and duration of extreme droughts (CSIRO 2015). Water shortages are expected to be coupled with water resources becoming increasingly contested, limiting the availability of irrigation water for dairying (Neal *et al.* 2009). Summer heat waves are also forecast to increase in frequency, duration, and intensity during the 21st century (Cowan *et al.* 2014). Broadly speaking, heat wave events are periods of consecutive abnormally hot days (Nairn and Fawcett 2013; Parker *et al.* 2014).

Summers in Tasmanian dairying regions are projected to become hotter and longer by the end of the 21st century. The frequency of days where maximum daily T_a exceeds 28°C is expected to increase in the Midlands and Derwent Valley of Tasmania (White *et al.* 2010). These two regions are currently experiencing dairy expansion (DairyTas 2016). Subsequently, it is questionable if the SE Australian dairy industry can continue to solely rely on perennial ryegrass and white clover as the main sources of home-grown forage.

2.4 ALLEVIATING THE CHALLENGE OF HOT AND DRY SUMMERS

This section reviews potential strategies for mitigating detrimental effects of hot and dry summer conditions on SE Australian dairy farming systems. Reviewed mitigation strategies either relate to management, or incorporating alternative species into the existing perennial ryegrass-white clover feed-base (Fulkerson and Doyle 2001).

2.4.1 Management

2.4.1.1 De-stocking

De-stocking is used to re-establish the equilibrium between feed demand and supply (Behnke and Kerven 1994). De-stocking is undesirable, as most stock (heifers and cows)

have a lifetime value exceeding their saleyard price [i.e. they produce saleable product (milk) over multiple years] (Kelleher *et al.* 2015). De-stocking strategies that minimise disruption of milking and replacement herds, include culling cows prior to summer (MacDonald and Penno 1998). 'Cow parking' can also be employed (Armstrong *et al.* 2005). 'Cow parking' is a lease agreement where the host farm covers all costs and receives all profits derived from accommodated cows (Armstrong *et al.* 2005). The feasibility of 'cow parking' is questionable, as unfavourable summer conditions for pasture production would generally be widespread, limiting the number of farms capable of accepting additional cows. Subsequently, de-stocking remains a least favoured response to summer feed deficits.

2.4.1.2 Fodder conservation

Surplus spring pasture is usually conserved as silage or hay for use during regular feed deficits, such as summer (Chapman *et al.* 2011; Özkan *et al.* 2015). Ensiling fodder is preferable, as silage has a higher digestibility and resultant milk yield potential than hay (Murphy *et al.* 2000).

Increasing fodder conservation in response to summer conditions becoming less conducive for perennial ryegrass-white clover growth has ramifications for the whole farm system. This is because high-quality conserved fodder production cannot be increased by harvesting at higher pasture covers (t DM/ha), but instead requires greater land allocation (Jacobs *et al.* 1998). Explanation is provided by increases in pasture cover being coupled with increased lignification of maturing fodder, and associated reduction in digestibility and ME content (Jacobs *et al.* 1998; Ombabi *et al.* 2001). Conserved fodder production may alternatively be increased by removing paddocks from the grazing rotation early in the growing season (late-winter to early-spring) to enable multiple cuts of fodder for conservation (Kaiser *et al.* 2004). However, on intensively stocked farms (≥3.0 cows/ha) paddocks are often not removed from the grazing rotation until late in the growing season when growth rates on the remaining grazing area can support the dairy herd (Thomson *et al.* 1984; Jacobs *et al.* 1998).

Increasing fodder conservation is not only impractical for intensively stocked dairy businesses, but incurs considerable costs (Holmes and Mathews 2001; Kaiser *et al.* 2004). Dry matter loss also occurs during the production of conserved fodder (Thomas and Mathews 1991), with feeding out incurring further losses of 2-25% (Moran 1996). It is

questionable if increasing conserved fodder production is a viable response to adverse summer conditions, particularly as the continued intensification of dairy production in Australia leads to higher stocking rates (Garcia and Fulkerson 2005).

2.4.1.3 Grazing management

During hot and dry summers, grazing management can affect growth and persistence of perennial ryegrass-white clover pastures (Brougham 1970; Frank *et al.* 1996). Summer grazing practices that leave higher stubble heights (height of stubble above the soil surface post-grazing) and longer intervals between grazing events have been advised. These practices are advocated because they limit depletion of plant NSC reserves, which are already reduced by the stresses of soil water deficit and supraoptimal temperatures (Waller and Sale 2001; Boschma *et al.* 2003). Management of perennial ryegrass-white clover pastures to limit further depletion of plant NSC reserves during hot and dry summers is imperative, as low or exhausted reserves result in plant death (Sullivan and Sprague 1949).

Longer intervals between grazing events enhance summer survival of perennial ryegrass and white clover under both rain-fed (Brink 1995; Garcia *et al.* 2010) and irrigated conditions (Lawson *et al.* 1997; McKenzie 1997; Donaghy and Fulkerson 2002). An extreme example is resting (grazing exclusion) a proportion of farm area in mid-summer (anthesis until seedhead maturity). This increases the resistance of perennial ryegrass swards to hot and dry summer conditions, by enabling plants to set seed for autumn recruitment (Waller *et al.* 1999; Waller and Sale 2001). Reproductive tiller development enhances individual plant survival while reducing nutritive value of grazeable herbage (Silsbury 1964; Waller *et al.* 1999; Waghorn and Clark 2004). Nutritive value reductions may be accepted in regions where hot and dry summer conditions significantly challenge perennial ryegrass persistence (Waller and Sale 2001).

Herbage removal via grazing can result in the elevation of plant crown (plant-soil interface) temperatures (Harrison *et al.* 2015). This is partly due to the reduced post-grazing canopy leaf area index (LAI) permitting more solar radiation (SR) and sensible heat interception at the crown (i.e. direct radiation heat exchange). This mechanism has been confirmed in winter wheat (*Triticum aestivum* L.) (Harrison *et al.* 2015), and used to explain the amplification of soil temperature close to the surface (pedoderm): (i) following and during

defoliation/grazing events (Bremer *et al.* 1998; Tanaka and Hashimoto 2006); and (ii) under fallow vs. pasture (Black and Aase 1988; Grant *et al.* 1995). In water-limited environments, greater SR interception at the canopy base can indirectly elevate crown temperature by reducing soil water content near the pedoderm (Black and Aase 1988; Matthew 1992; Liu *et al.* 2011). This is because reductions in soil water content can make soil surrounding the crown more susceptible to temperature increases (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015), while reducing the potential for evaporative cooling (Bremer *et al.* 2001). The elevation of crown temperature during periods of supraoptimal temperature stress may negatively affect the growth and persistence of perennial ryegrass-white clover pastures, due to: (i) indeterminate meristematic tissues (apical meristem) being located at the crown during vegetative growth phases (Rumball 1986; Korte *et al.* 1987; Yang *et al.* 1998); and (ii) potentially exacerbating the depletion of NSC reserves (White 1973). Subsequently, it may be advantageous during periods of supraoptimal temperature stress to reduce the intensity of grazing events (i.e. leaving a higher post-grazing LAI) or avoid grazing altogether. Further research is needed to validate this conclusion.

Grazing management outside of the summer period can affect the summer survival of perennial ryegrass. Short intervals between winter grazing events reduce root system size (Donaghy *et al.* 1997), thereby limiting the ability of plants to extract water during soil water deficits. Conversely, continuous grazing over spring has been advocated for delaying anthesis until late spring, so basal tiller buds encounter hot and dry conditions and become dormant (Waller and Sale 2001). This practice delays tiller emergence until autumn when more favourable weather conditions prevail, thereby increasing tiller survival (McKenzie 1997; Waller and Sale 2001). Despite continuous grazing being seldom practiced in dairy farming systems (Kemp *et al.* 2000), anthesis can be delayed by reducing the interval between grazing events on a proportion of a farm. This is possible if considerable areas are removed from the grazing rotation during spring for fodder conservation (Thomson *et al.* 1984).

2.4.1.4 Irrigation

Irrigation is widely used in SE Australian dairy systems to mitigate detrimental effects of soil water deficit on pasture production (ABS 2015). Research has highlighted the benefits of frequent irrigation schedules for maximising perennial ryegrass-white clover yields

(Dunbabin *et al.* 1997; Ward and Burch 1999; Jacobs and Ward 2004; Sumanasena *et al.* 2011). Frequent irrigation schedules are most beneficial during summer, when evapotranspiration is greatest (Kelly *et al.* 2005; Greenwood *et al.* 2006). Irrigating frequently to replenish soil water content to field capacity is advantageous for pastures experiencing supraoptimal temperature stress (Julander 1945). Advantages include: (i) maintaining plants with a high capacity to dissipate excess heat via transpiration (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004); and (ii) reducing the soils susceptibility to temperature change (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015). Irrigation, applied as a spray, can also depress plant temperatures by conduction (transfer of heat from plant to water), and from evaporation on the plant surfaces (Kliewer and Schultz 1973; Aljibury *et al.* 1975).

The ability of irrigated temperate grasses to tolerate supraoptimal temperatures may be enhanced by prior exposure to mild soil water deficits, via the process of drought preconditioning-enhanced heat tolerance (Jiang and Huang 2000, 2001a; Peng *et al.* 2012). Subsequently, irrigation schedules imposing spring soil water deficits may limit the detrimental effects of hot summer conditions on plant survival and performance (Jiang and Huang 2000). Drought preconditioning-enhanced heat tolerance may be an example of cross-tolerance, based on commonalities between the stresses of supraoptimal temperatures and soil water deficit (Arora *et al.* 1998). Alternatively, drought preconditioning may induce a phenomenon termed acquired heat tolerance (DiMascio *et al.* 1994; Xu *et al.* 2006). Acquired heat tolerance describes the enhanced tolerance of plants to supraoptimal temperatures following exposure to sub-lethal temperatures (Minner *et al.* 1983; White *et al.* 1988; DiMascio *et al.* 1994). Sub-lethal temperatures could be induced by exposing plants to mild soil water deficits that restrict transpirational cooling (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004).

2.4.1.5 Soil fertility

The survival of temperate grasses during hot summers can be affected by timing and rate of N fertiliser applications (Carroll 1943; Lucanus *et al.* 1960; Fulkerson *et al.* 1993). Applying high N rates during hot summers can negatively affect survival of perennial ryegrass, and other temperate grasses (Carroll 1943; Lucanus *et al.* 1960). High N levels may reduce plant survival by facilitating shoot growth to the detriment of NSC reserves already depleted by

the high respiratory demands of plants subjected to supraoptimal temperature stress (Alberda 1965; Totten *et al.* 2007; Wang *et al.* 2014). Conversely, multiple applications of N prior to periods of supraoptimal temperature stress can enhance grazed perennial ryegrass survival (Fulkerson *et al.* 1993). This result is attributed to the higher concentration of N reserves supporting increased N requirements during the early phases of regrowth (Volenec *et al.* 1996).

The role of soil fertility in mitigating detrimental effects of soil water deficit on pastures is less researched. One key finding from the limited available information is the positive relationship between phosphorus (P) supply and white clover drought tolerance (Singh *et al.* 1997; Singh and Sale 1998, 2000). High P rates (50 vs. 10 kg P/ha) enhance root permeability and subsequent ability of white clover plants to extract soil water (Singh and Sale 1998, 2000). Greater root conductivity is attributed to higher coarse root length density and mean xylem diameter (Singh and Sale 2000).

2.4.2 Alternative species

2.4.2.1 Summer-dormant perennial forages

Summer-dormant ecotypes of cocksfoot (*Dactylis glomerata* L.), tall fescue (*Festuca arundinacea* Schreb.), perennial ryegrass, and phalaris (*Phalaris aquatica* L.) can be grown in rain-fed grazing systems to enhance pasture persistence (Silsbury 1969; Norton *et al.* 2006a; Norton *et al.* 2006b; Norton *et al.* 2012). Summer dormancy is a hormonally controlled endogenous process, independent of soil water availability. It is induced by increases in photoperiod and temperature that signal the onset of summer (Volaire and Norton 2006). Completely summer-dormant ecotypes of cocksfoot (cv. Kasbah®) cease growth, with all above-ground tissue senescing and surviving organs becoming dehydrated (Norton *et al.* 2006a). Incompletely summer-dormant ecotypes of tall fescue (cv. Flecha®), perennial ryegrass (cv. Medea®) and phalaris (cv. Atlas PG®) experience growth reductions, with moderate levels of above-ground tissue senescence (Norton *et al.* 2006b; Volaire *et al.* 2009; Norton *et al.* 2012; Hussain 2013).

Summer dormancy enables plants to avoid and resist supraoptimal temperature and soil water deficit stress (Nie and Norton 2009). Severe soil water deficits have had no effect on

the persistence of summer-dormant cocksfoot and tall fescue ecotypes, but reduced the basal cover of their summer-active contemporaries by 22% and 25%, respectively (Norton *et al.* 2006a; Norton *et al.* 2006b).

Despite aforementioned benefits, monocultures of summer-dormant ecotypes are unsuitable for SE Australian dairy systems. This is because the profitability of these dairy systems depends on their capacity to fill ruminant feed requirements with a year-round source of high-quality home-grown feed (Chapman *et al.* 2011). Summer-dormant pasture ecotypes are more suited to extensive grazing enterprises that infrequently renovate pastures (once in every 20 years), as they generate lower levels of income/ha (Browne *et al.* 2013; Malcolm *et al.* 2014). Summer-dormant ecotypes potentially could be incorporated into the SE Australian dairy feed-base, if sown in mixtures with compatible summer-active plants (Norton 2011).

2.4.2.2. Grazeable annual summer forage crops

Grazeable annual summer forage crops can increase high quality home-grown feed availability over summer, provided water is available (Eckard *et al.* 2001). Being grazeable, they eliminate costs and losses incurred by producing and feeding out conserved fodder (Chapman *et al.* 2014). Annual summer forage crops are often included in pasture renovation programs to offset establishment costs (Jacobs *et al.* 2001; Jacobs *et al.* 2006).

Grazeable annual summer forage crops include turnips (*Brassica rapa* L. var. *rapa*), rape (*B. napus* L. var. *napus*), kale (*B. oleracea* L.), hybrid brassica (*B. campestris* L. x *B. napus* L.), millet [Japanese millet, *Echinochloa esculenta* (A. Braun) H. Scholz; pearl millet, *Cenchrus americanus* L. Morrone], and sorghum (*Sorghum bicolor* L.). Of these species, *Brassica* species are the most commonly grown in SE Australia, being regularly sown on more than 70% of Victorian and Tasmanian dairy farms (Eckard *et al.* 2001).

Turnips are the most popular *Brassica* species, justified by their low cost of production and high nutritive value (Eckard *et al.* 2001; Rawnsley 2007). Turnip production costs can be variable, with greater DM yields (t DM/ha) reducing growing costs (Jacobs *et al.* 2001). Dry matter yields are substantially affected by amount of applied water (rainfall or irrigation) (Jacobs *et al.* 2001), with irrigation achieving yield increases of 3.8-6.5 t DM/ha (Neilsen *et*

al. 2000; Eckard *et al.* 2001). Therefore, the suitability of turnips for rain-fed dairy systems is questionable.

More recently, *Brassica* species capable of post-grazing regrowth (e.g. rape) have become popular, due to increasing the period of feed availability over the summer (Ward and Jacobs 2013). Grazing these species requires knowledge of anticipated soil water conditions adding to their management complexity. If soil water availability is expected to: (i) become growth limiting, a severe initial grazing is recommended; or (ii) not prohibit growth, a moderate grazing intensity should be achieved to maximise retention of axillary buds for regrowth (Ward and Jacobs 2013). Further management complexity resulting from the inclusion of *Brassica* species into dairy systems relates to a variety of ruminant health issues if cows are not correctly acclimated (Morton and Campbell 1997).

The role of annual summer forage crops in SE Australian intensive grazing enterprises remain restricted to the permanent pasture renovation cycle, limiting their value in mitigating summer feed deficits. This is justified by their: (i) limited suitability for rain-fed systems (Eckard *et al.* 2001); (ii) greater growing season production costs relative to perennials (Macleod *et al.* 1993); and (iii) added management complexity in the case of *Brassica* species (Morton and Campbell 1997; Ward and Jacobs 2013).

2.4.2.3 Subtropical (C_4) perennial forages

Subtropical perennial forages have been advocated as a solution for overcoming summer feed deficits (Nie *et al.* 2008; Ward *et al.* 2013). This is partly due to their maximum photosynthetic rate occurring at higher temperatures than their C_3 counterparts (30-40˚C vs. 10-25˚C) (Johnston 1996). In addition, C_4 plants have higher water-use efficiencies (Neal *et al.* 2011), due to their Kranz anatomy, which allows leaves to saturate carboxylating enzymes (RuBisCO and phosphoenolpyruvate carboxylase) with carbon dioxide at low stomatal conductance levels. This maximises the efficiency of photosynthesis during soil water deficits, without excessive water loss (Sage 2004).

Species commonly used by Australian dairy farmers in the subtropics include, kikuyu (*Pennisetum clandestinum* Hochst. ex Chiov.), pangola grass (*Digitaria eriantha* Steud.), paspalum (*Paspalum dilatatum* Poir.), Rhodes grass (*Chloris gayana* Kunth), and setaria (*Setaria sphacelata* var. *sericea*) (Fulkerson 1997). Of these species, only kikuyu and

paspalum can survive the frosts and cold wet conditions characteristic of SE Australian winters (Davies and Forde 1991; Cavaco *et al.* 2003; Moore *et al.* 2006; Moore *et al.* 2014). Kikuyu's rhizomatous growth habit enables the species to survive winter, with plants resuming growth from rhizomes in spring (Nie *et al.* 2008; Moore *et al.* 2014).

The persistence of kikuyu can be limited, when grown in mixed swards with C_3 forages (Clark *et al.* 2013). This is due to kikuyu's sensitivity to shading by C_3 forages during spring peak production, a sensitivity explained by the low chlorophyll content in kikuyu's shoots (Ludlow *et al.* 1988). Another limitation of both kikuyu and paspalum is their low nutritive value (Stockdale 1999; Garcia *et al.* 2014). This is due to high fibre content limiting digestibility and ruminant intake (Brown 1999). The low nutritive value of kikuyu and paspalum, combined with their limited out of season growth, hinders their incorporation into the SE Australian dairy feed-base.

2.4.2.4 Summer-active temperature (C_3) perennial forages

Potentially, summer feed deficits could be alleviated by incorporating alternative summer-active temperate (C_3) perennial forages into the feed-base, which are more tolerant of hot and/or dry conditions than perennial ryegrass and white clover (Chapman *et al.* 2008b). Alternative summer-active temperate perennial forages advocated for inclusion into SE Australian grazing systems include: (i) summer-active (continental-type) ecotypes of cocksfoot and tall fescue (Lolicato and Rumball 1994; Reed *et al.* 2008; Clark *et al.* 2013); and (ii) inherently summer-active species, including prairie grass (*Bromus catharticus* Vahl.) (Turner *et al.* 2006b, 2006a), lucerne (*Medicago sativa* L.) (Humphries 2012; Clark *et al.* 2013), red clover (*Trifolium pratense* L.) (Charlton and Stewart 1999; Chapman *et al.* 2008b), chicory (*Cichorium intybus* L.) (Dear *et al.* 2008), and plantain (*Plantago lanceolata* L.) (Stewart 1996a; Chapman *et al.* 2008b). These species potential role in the SE Australian dairy feed-base is discussed in the accompanying section.

2.5 SUMMER-ACTIVE TEMPERATE (C_3) PERENNIAL FORAGES

2.5.1 Suitability for inclusion into the current feed-base

Summer-active temperate perennial forages suitability for SE Australian dairy farming systems not only relates to their potential role in mitigating summer feed deficits, but also their ease of incorporation into the existing feed-base. This is due to these species being perennial, grazeable, and nutritious. Rawnsley *et al.* (2013) concluded the perenniality and grazeable nature of the current feed-base underpins the well-known positive relationship between home-grown forage use and farm profitability in Australia.

Summer-activity has the disadvantage of limiting plant persistence (Nie *et al.* 2008), as shown by comparisons between summer-active and summer-dormant ecotypes of cocksfoot and tall fescue (Norton *et al.* 2006a; Norton *et al.* 2006b). Dairy and other intensive grazing industries capable of generating high levels of income/ha may overlook persistence in favour of production (Bryan *et al.* 2009; Browne *et al.* 2013). This is particularly pertinent during seasons traditionally associated with feed deficit (e.g. summer), when feed value is at a premium (Young *et al.* 2010; Chapman *et al.* 2011).

2.5.1.1 Perenniality

Perennial forages have economic and environmental advantages over their annual counterparts (e.g. summer forage crops). Economic advantages arise from less frequent re-establishment requirements, thereby limiting: (i) cultivation, sowing, and establishment related costs per growing season; and (ii) opportunity costs incurred by the removal of land from the grazing rotation during establishment (Macleod *et al.* 1993). Environmental benefits, outlined by both Cransberg and McFarlane (1994) and Bell *et al.* (2006) include: (i) reduced erosion risk, owing to greater annual groundcover (Silburn *et al.* 2007); (ii) greater soil organic carbon stocks, and concomitant soil health (Poeplau *et al.* 2011; Badgery *et al.* 2013); (iii) lower dryland salinity risk, due to reduced deep-drainage (Ward *et al.* 2014); and (iv) less nitrate leaching, and subsequent soil acidification (Williams 1980; Dear *et al.* 2009).

2.5.1.2 Grazeable

Grazeable forages are synonymous with grazing ruminant systems. These systems have lower feed costs per unit of ruminant production than cropping based systems employing 'cut and carry' (Gloy *et al.* 2002; White *et al.* 2002). 'Cut and carry' incurs a higher feed cost, due to the required investment and ongoing operational expenses related to: (i) harvesting, storage, and feed delivery equipment, and the indirect cost of DM losses during these processes; and (ii) ruminant housing infrastructure (e.g. feedpads and barns) (Gloy *et al.* 2002; White *et al.* 2002).

2.5.1.3 High nutritive value

Aforementioned summer-active temperate perennial grasses and legumes can support the nutritional requirements (protein and ME) of a 600 kg dairy cow producing 2.2 kg of milksolids/day, provided DM intake is sufficient (Fulkerson *et al.* 2007). This contradicts the misconception that cocksfoot and tall fescue are of insufficient nutritive value for dairy cattle. Further evidence of their adequate nutritive values are provided by both Turner *et al.* (2006b) and Raeside *et al.* (2012a).

The adoption of lucerne and red clover in SE Australian dairying regions can be hampered by ruminant health concerns. One concern, common to white clover, is the potentially fatal condition frothy bloat (Wang *et al.* 2012). This barrier can be overcome, at a cost, with a variety of chemical preventatives (e.g. alcohol ethoxylate) (Barr and Day 1977). Another ruminant concern historically relating to red clover is animal infertility, due to herbage containing high levels of formononetin, a phyto-oestrogen compound (Anderson 1978; McDonald *et al.* 1994). Modern stoloniferous cultivars (Astred® and Rubitas®) more suited to grazing systems, contain low formononetin levels (Smith and Bishop 1993; Hall and Hurst 2013), effectively eliminating this problem.

Chicory and plantain can produce herbage of high nutritive value, characterised by a low neutral-detergent fibre (NDF) content and being mineral-rich (Sanderson *et al.* 2003; Pirhofer-Walzl *et al.* 2011). However, during autumn and winter their herbage contains toxic nitrate levels, necessitating that dairy cow intake does not exceed 4-5 kg of DM/day (Fulkerson *et al.* 2008). Effectively incorporating these forbs into mixed pastures overcomes

this challenge (Fulkerson *et al.* 2008). Chicory has also been criticised for containing sesquiterpene lactones (lactucin and lactucopicrin), compounds which can cause milk tainting if large quantities are consumed (Rumball *et al.* 2003a). This challenge has been overcome following the release of the cultivar, Choice®, which contains only 70-85% of the sesquiterpene lactone levels present in the original cultivar, Puna® (Rumball *et al.* 2003a).

2.5.2 Superior summer production

2.5.2.1 Ruminant livestock

Experiments evaluating the effect of alternative summer-active temperate perennial forages on milk production in SE Australia have focused on changes to the nutritional profile of grazed pasture. This is evidenced by pasture allowances (Table 2.1), having approached or exceeded maximum daily DM intakes achievable by the studied cows (3.76% live weight) (Kolver and Muller 1998). One such experiment reported daily milksolids production, from autumn-calving cows declined by a lesser factor, when cows grazed a diverse mixture of summer-active temperate perennial forages relative to perennial ryegrass-based swards (Table 2.1) (Chapman *et al.* 2008b). Differences in milksolids production resulted from the more constant nutritive value of herbage produced by the diverse mixture limiting the decline in milksolids production between spring and summer (Chapman *et al.* 2008b).

Consumption of chicory has had conflicting effects on summer milk production in south-western Victoria (Table 2.1). Dairy cows grazing a binary mixture of chicory and white clover produced 83% more milksolids/day than those grazing a perennial ryegrass-based sward (Chapman *et al.* 2008b). In contrast, daily milk yield of dairy cows grazing a binary mixture of perennial ryegrass and chicory did not significantly differ from their contemporaries grazing perennial ryegrass monocultures (Muir *et al.* 2015). The positive production response reported by Chapman *et al.* (2008b) resulted from the sward being in its first year of production, with all chicory plants being vegetative (Hare *et al.* 1990). Conversely, in the study by Muir *et al.* (2015) chicory plants were in a reproductive state (second growing season). Reproductive development reduces chicory's nutritive value due to the development of hollow fibrous stems (Clark *et al.* 1990; Lee *et al.* 2015a).

Other studies have sought to capture ruminant production benefits resulting from the superior summer growth of alternative summer-active temperature perennial forages (Table 2.2). Kenny and Reed (1984) employed set stocking to show lucerne could increase summer-autumn lamb weight gains in south-western Victoria (Table 2.1). However, production benefits did not result from growth differences of the pasture species, but rather from the higher crude protein and lower NDF content of lucerne relative to perennial ryegrass (Kenny and Reed 1984).

Table 2.1 Examples of Australian experiments comparing the productivity of ruminants grazing traditional perennial ryegrass-based swards vs. alternative summer-active temperate perennial forages. Species are denoted as follows: (i) chicory (*Cichorium intybus* L.), CH; (ii) cocksfoot (*Dactylis glomerata* L.), CF; (iii) lucerne (*Medicago sativa* L.), LU; (iv) plantain (*Plantago lanceolata* L.), PL; (v) perennial ryegrass (*Lolium perenne* L.), PRG; (vi) red clover (*Trifolium pratense* L.), RC; (vii) subterranean clover (*Trifolium subterraneum* L.), SB; (viii) tall fescue (*Festuca arundinacea* Schreb.), TF; and (ix) white clover (*Trifolium repens* L.), WC. Other abbreviations include: (i) autumn-calving, AC; (ii) spring-calving, SC; and (iii) no change ($P \geq 0.05$), NC.

	Sward composition			Daily ration (kg of dry matter/ruminant)		Ruminant production		
Region	**Traditional**	**Alternative/s**	**Livestock**	**Pasture**	**Supplement**	**Metric**	**Change in daily yield**	**Source**
Tasmania	PRG	PRG, WC, PL	SC dairy cow	20	Pellets, 2-4	Milk fat Milk protein	NC, 0.9 vs. 0.9 kg/cow NC, 0.7 vs 0.7 kg/cow	(Pembleton *et al.* 2016)
South-western Victoria	PRG, WC, SB	TF, CF, WC, RC, CH CH & WC	AC dairy cow	45-60	None	Milksolids	Increase, 0.8 vs 1.0 kg/cow Increase, 0.8 vs. 1.4 kg/cow	(Chapman *et al.* 2008b)
	PRG	PRG & CH	AC dairy cow	PRG, 55.5 PRG & CH, 38.8	Pellets, 4 LU hay, 5.5	Milk yield	NC, 12.0 vs. 13.0 kg/cow	(Muir *et al.* 2015)
	PRG & SB	LU	Weaner sheep	Fixed area	None	Live weight	Increase, -6 vs 59 g/sheep	(Kenny and Reed 1984)

2.5.2.2 Pasture growth

Alternative summer-active temperate perennial forages can out-yield perennial ryegrass-based swards during summer, without compromising annual production (Table 2.2). Both lucerne and summer-active tall fescue, when grown as monocultures or as a major component of mixed swards, can out-yield perennial ryegrass on both a summer and often an annual basis (Table 2.2) (Greenwood *et al.* 2006; Tharmaraj *et al.* 2008; Lawson *et al.* 2009; Ward *et al.* 2013; Raeside *et al.* 2014). Superior summer yields are attributed to their: (i) deeper-root systems enabling extraction of soil water stores to depth (Garwood and Sinclair 1979; Borg and Grimes 1986); (ii) responsiveness to summer rainfall events (Knox *et al.* 2006; Lawson *et al.* 2007; Raeside *et al.* 2014); and (iii) greater tolerance than perennial ryegrass of supraoptimal temperatures (Jiang and Huang 2001b; Callow *et al.* 2003; Zaka *et al.* 2014). Other grasses with potential to increase summer growth include summer-active cocksfoot and prairie grass (Table 2.2).

Pasture swards containing chicory and plantain can out-yield perennial ryegrass-dominated swards during summer in SE Australia (Table 2.2) (Raeside *et al.* 2014). Chicory may not out-yield perennial ryegrass on an annual basis due to being virtually winter dormant (Rumball 1986; Pembleton 2015). Despite breeding efforts to improve chicory's winter activity (Rumball *et al.* 2003a; Rumball *et al.* 2003b), chicory's growing season in the southern hemisphere remains restricted to the spring-autumn period (Li and Kemp 2005; Li *et al.* 2010). Chicory may be used as a speciality pasture species to improve summer ruminant productivity.

Table 2.2 Examples of south-eastern Australian experiments evaluating the growth of traditional perennial ryegrass-based swards vs. alternative summer-active temperate perennial forages. Species are denoted as follows: (i) chicory (*Cichorium intybus* L.), CH; (ii) cocksfoot (*Dactylis glomerata* L.), CF; (iii) lucerne (*Medicago sativa* L.), LU; (iv) prairie grass (*Bromus catharticus* Vahl.), PG; (v) plantain (*Plantago lanceolata* L.), PL; (vi) perennial ryegrass (*Lolium perenne* L.), PRG; (vii) red clover (*Trifolium pratense* L.), RC; (viii) subterranean clover (*Trifolium subterraneum* L.), SB; (ix) tall fescue (*Festuca arundinacea* Schreb.), TF; and (x) white clover (*Trifolium repens* L.), WC. Other abbreviations include: (i) irrigated, I; (ii) rain-fed, RF; (iv) winter-activity rating [range from winter dormant (3-4) to highly winter-active (8-10)], WA; and (iii) no change ($P \geq 0.05$), NC.

		Sward composition			Change in dry matter yield		
Region	**Irrigation**	**Traditional**	**Alternative/s**	**Years**	**Summer/summer-autumn**	**Annual/growing season**	**Source**
Tasmania	I & RF	PRG	PL	2	NC year 1, Increase year 2 (64%)	NC	K. G. Pembleton, unpublished study
	RF	PRG	CF	1	Increase (67%)	NC	(Turner *et al.* 2006a)
			PG		Increase (52%)	Increase (41%)	
Northern Victoria	I	PRG	LU (WA8)	2	Increase (≥140% both years)	NC year 1, Increase year 2 (13%)	(Greenwood *et al.* 2006)
			TF		Increase (≥33% both years)	NC year 1, Increase year 2 (25%)	
	I	PRG & WC	LU (WA5)	2	Increase (≥90% both years)	NC year 1, Increase year 2 (30%)	(Lawson *et al.* 2009)
			TF & WC		Increase year 1 (69%), NC year 2	NC year 1, Increase year 2 (15%)	
South-western Victoria	RF	PRG & SB	CH & SB	1	Increase (30%)	-	(Raeside *et al.* 2014)
			LU (WA7)		Increase (36%)	-	
	RF	PRG, WC, SB	TF, CF, WC, RC, CH	3	Increase (51%)	NC	(Tharmaraj *et al.* 2008)
	RF	PRG, WC, SB	LU (WA7), WC, SB	3	Increase (≥1567%) year 1 & 3, NC year 2	NC	(Ward *et al.* 2013)

2.5.3 Rational for superior summer growth

2.5.3.1 Soil water deficit

Advantages of aforementioned summer-active temperate perennial forages for rain-fed dairy farming systems include their capacity to avoid/delay detrimental effects of soil water deficit (dehydration) (Volaire *et al.* 2009). Many of these species possess deeper and more extensive root systems than either perennial ryegrass or white clover (Wilman *et al.* 1998; Charlton and Stewart 1999; Ward *et al.* 2013). Possessing extensive root systems enables these plants to avoid/delay dehydration by accessing soil water stores at greater depth (Farooq *et al.* 2009; Comas *et al.* 2013).

Many deeper rooted species such as lucerne, red clover, and chicory possess tap roots (Frame 2004; Li and Kemp 2005). Of these tap-rooted species, lucerne is the most drought tolerant, with a capacity to develop a deeper root system than either red clover or chicory (Humphries and Auricht 2001; Brown *et al.* 2005). Despite this advantage, widespread adoption of lucerne in SE Australian dairying regions has been hampered by the species' sensitivity to both aluminium toxicity (i.e. acidic soils) and waterlogging (Dear and Ewing 2008; Smith and Fennessy 2011). Chicory offers an alternative to lucerne in the high-rainfall zone of SE Australia, owing to this species greater tolerance of aforementioned abiotic stresses (Ward *et al.* 2013). Plantain also possesses a tap-root, but has a similar rooting depth to perennial ryegrass (Nie *et al.* 2008; Cranston *et al.* 2016). Despite this, plantain growth during dry summer conditions is superior to perennial ryegrass (Stewart 1996a).

Summer-active tall fescue not only develops a deeper root system than perennial ryegrass (Garwood and Sinclair 1979; Nie *et al.* 2008), but has superior waterlogging tolerance (Rogers and Davies 1973). In environments where summer rainfall is limited or unreliable, summer-active tall fescue should be grown on heavy textured (clay-rich) soils that become waterlogged during winter/early-spring, as accumulated soil water stores support early summer growth (Raeside *et al.* 2012b). Another alternative species, prairie grass, develops an extensive root system at depth (0.8 m) (Shaffer *et al.* 1994), but is less tolerant to intensive grazing in wet conditions (Charlton and Stewart 1999). Summer-active cocksfoot is more tolerant than perennial ryegrass to dry summer conditions (Neal *et al.* 2009; Turner *et al.* 2012), despite both species having a similar depth and distribution of rooting (Nie *et al.* 2008). Cocksfoot can extract soil water to lower matric potentials than perennial ryegrass

(e.g. -1.43 vs. -0.73 MPa, respectively), which allows it to grow in harsher environments (Volaire *et al.* 1998).

Summer-active species can respond to summer rainfall events. Chicory and lucerne have a greater capacity than perennial ryegrass to grow after rainfall events during hot and dry summers (Lawson *et al.* 2007; Raeside *et al.* 2014). Red clover growth is purported to be highly responsive to summer rainfall events (Dairy Australia 2010), with a similar response presumed for plantain, based on this species' high level of summer-activity (Nie *et al.* 2008). All candidate grasses are purported to have a 'very good' (prairie grass) to 'excellent' (summer-active ecotypes of cocksfoot and tall fescue) responsiveness to summer rainfall (Knox *et al.* 2006; Lawson *et al.* 2007; Norton *et al.* 2008).

2.5.3.2 Supraoptimal temperature

Knowledge of the candidate species tolerance to supraoptimal temperatures (T_a ≥30˚C) is often either limited or anecdotal, with available evidence presented below. An understanding of their potential tolerance is required to assist dairy farmers in selecting forages that mitigate detrimental effects of hot summer conditions on home-grown feed production. This necessitates an evaluation of candidate summer-active temperate perennial forages ability to tolerate supraoptimal temperatures. Tolerance in the context of dairy farming systems is defined as a species ability to grow during or shortly after the cessation of supraoptimal temperature stress.

Legumes

Lucerne is presumed to be tolerant of supraoptimal temperature stress despite having a relatively low optimum T_a of 22˚C (Fick *et al.* 1988). Presumed tolerance is based on lucerne's persistence in environments where T_a can exceed 50˚C (Barnes and Sheaffer 1995). Under irrigation, lucerne growth is less affected by supraoptimal temperatures than either white or red clover (Al-Ghumaiz 2012). Lucerne's germplasm contains considerable diversity for supraoptimal temperature stress tolerance (Han *et al.* 2008; Liu *et al.* 2013; An *et al.* 2014).

Greater uncertainty surrounds red clover's tolerance of supraoptimal temperatures, with red clover growth optimal at an T_a of 20-25˚C, with temperature limits of 7-40˚C (Frame 2004).

However, T_a ≥30˚C reduce red clover's NSC reserves via increased dark respiration rates, which can compromise plant survival in the following winter (Frame 2004; Kelly *et al.* 2005). Despite these qualifications, red clover is known to be more tolerant of supraoptimal temperatures than white clover (Zhang *et al.* 2009; Al-Ghumaiz 2012).

Non-leguminous forbs

Plantain appears to be tolerant of supraoptimal temperature stress, but to date, most available evidence is anecdotal (Sagar and Harper 1964; Stewart 1996a). Evidence includes this species prevalence in many hot and subtropical climates (Sagar and Harper 1964). Conversely, Teramura *et al.* (1981) claimed plantain was 'poorly' adapted to hot conditions as increasing diurnal T_a from 26˚C to 29˚C reduced leaf elongation rates. Teramura and Strain (1979) found plantain's photosynthetic capacity was reduced by increases in leaf temperature above 23˚C.

Contrasting temperature responses have been reported for chicory, with available literature restricted to vegetable-type cultivars. Irrigated chicory shoot growth is known to be resilient to supraoptimal temperature stress, being unaffected by increases in diurnal T_a from 20-30˚C (Lee *et al.* 2013). However, Mathieu *et al.* (2014) found that chicory root growth under a 35/28˚C temperature regime was less than when maintained under a constant 17˚C. This suggests that supraoptimal temperature stress may compromise a chicory plant's capacity to extract soil water from depth.

Due to these conflicting findings, further research is required to confirm the propensity of these forbs to tolerate supraoptimal temperature stress.

Grasses

Authors have claimed prairie grass, like many other *Bromus* spp. of agricultural importance, is tolerant of supraoptimal temperatures (Stewart 1996b; Charlton and Stewart 1999). Claims are based on the species origin in the Pampas region of Argentina and Uruguay (South America), a region characterised by hot summers (Stewart 1996b). In subtropical Australia the capacity of prairie grass to out-yield perennial ryegrass is attributed to the species ability to accumulate plant NSC reserves during spring (Lowe *et al.* 1999; Fulkerson *et al.* 2000). These NSC reserves may support the elevated respiratory demands of prairie grass plants during hot summers. Fulkerson *et al.* (2000) advocated having long intervals between spring grazing events (i.e. grazing at 4 leaves/tiller) to maximise the accumulation

of plant NSC reserves (Fulkerson *et al.* 2000). This practice further enhances the persistence of prairie grass swards experiencing hot summers by: (i) enabling considerable seed set; and (ii) permitting the development of a mat of senesced material at the pedoderm to delay seedling emergence until sufficient decomposition has occurred by autumn when cooler conditions prevail (Fulkerson *et al.* 2000; Neal *et al.* 2009).

Summer-active tall fescue ecotypes are known to be more resilient than perennial ryegrass to supraoptimal temperature stress (Milne 2011; Raeside *et al.* 2012b). This is partly based on the superior summer yield potential of tall fescue in irrigated environments, where T_a regularly exceed 30-35˚C (Lowe and Bowdler 1995; Callow *et al.* 2003; Greenwood *et al.* 2006). Tall fescue is also more tolerant than perennial ryegrass of hot and dry conditions (Jiang and Huang 2001b). Wallner *et al.* (1982) found the supraoptimal temperature tolerance of tall fescue and perennial ryegrass leaves *in vitro* did not differ. Jiang and Huang (2001b) attributed the superior supraoptimal temperature tolerance of tall fescue *in situ*, to the species deeper and more extensive root system. This explains tall fescue's greater transpirational cooling capacity than seen in perennial ryegrass (Jiang and Huang 2001b).

In contrast to both prairie grass and tall fescue, summer-active cocksfoot ecotypes' ability to tolerate supraoptimal temperatures has received little attention. Under irrigation, Mitchell (1956) reported the optimum T_a for shoot growth differed minimally between cocksfoot and perennial ryegrass (21.1˚C and 20˚C, respectively). Despite this, cocksfoot shoot growth was greater than perennial ryegrass at T_a of 29.4˚C and 35˚C (Mitchell 1956). Cocksfoot also has a higher optimum root growth soil temperature than perennial ryegrass (27.7˚C vs. 20˚C) (Davidson 1969). Based on these findings, cocksfoot is suggested to be more tolerant than perennial ryegrass to supraoptimal temperature stress.

2.6 CONCLUSION/FUTURE RESEARCH AVENUES

This review has identified summer-active temperate perennial forages with potential to increase summer home-grown feed production in SE Australian dairying regions. Their suitability for incorporation into the current feed-base is evidenced by their perennial, grazeable, and high forage value. The high summer yield potential of these summer-active temperate perennial forages is associated with superior tolerance to hot and/or dry conditions. However, knowledge of these species tolerance to supraoptimal temperature stress is either

limited or anecdotal. An evaluation of their tolerance to supraoptimal temperature stress is required to identify the most promising species for regions where supraoptimal temperatures constrain summer home-grown feed production.

The role of management in maximising summer growth for promising summer-active temperate perennial forages also warrants investigation. Justification is provided by the identification in this review of grazing, irrigation, and soil fertility management practices substantially affecting growth and survival of pastures during hot and dry summers. Of interest is the effect of grazing upon pasture species crown temperatures and the interacting influences of irrigation management regimes.

Chapter 3: **Potential of summer-active temperate (C_3) perennial forages to mitigate the detrimental effects of supraoptimal temperatures on summer home-grown feed production in south-eastern Australian dairying regions**

3.1 OVERVIEW OF CHAPTER 3

In the literature review (Chapter 2), summer-active temperate (C_3) perennial forages with potential to increase summer home-grown feed production in south-eastern Australian dairying regions are identified. Current knowledge of these species tolerance to supraoptimal temperature stress is either limited or anecdotal. An understanding of their potential tolerance to supraoptimal temperature stress is required to assist dairy farmers in selecting forages that mitigate the detrimental effects of hot summer conditions on pasture production. Research reported in this chapter (Chapter 3) tested the hypothesis some of these species are more tolerant of supraoptimal temperature stress than perennial ryegrass (*Lolium perenne* L.). The research was conducted under glasshouse conditions, with supraoptimal temperature stress imposed under both irrigated and non-irrigated conditions.

3.2 ABSTRACT

In many south-eastern Australian dairying regions, supraoptimal ambient temperatures (T_a >30˚C) often challenge the perennial ryegrass (*Lolium perenne* L.)-dominated feed-base during the summer months. A glasshouse experiment was undertaken to identify alternative summer-active temperate (C_3) perennial forages more tolerant of supraoptimal temperature stress (day/night T_a of 38/25˚C) than perennial ryegrass. Supraoptimal temperature stress was imposed both with and without irrigation. Chicory (*Cichorium intybus* L.) was the only species to survive 18 days of combined supraoptimal temperature stress and non-irrigation. Lucerne (*Medicago sativa* L.), plantain (*Plantago lanceolata* L.), and tall fescue (*Festuca arundinacea* Schreb.) survived 12 days of this treatment. Twelve days of exposure to these conditions caused death of perennial ryegrass, prairie grass (*Bromus catharticus* Vahl.), cocksfoot (*Dactylis glomerata* L.), birdsfoot trefoil (*Lotus corniculatus* L.), and red clover (*Trifolium pratense* L.). Irrigation (daily to through drainage) mitigated detrimental effects of imposed supraoptimal temperature stress on the growth and survival of all species. Chicory and to a lesser extent lucerne, plantain, and tall fescue may have a role to play in south-eastern Australian dairying regions, where supraoptimal temperature stress is a frequent and ongoing issue.

3.3 KEYWORDS

Chlorophyll fluorescence, drought, heat stress, heat tolerance, thermotolerance, water stress

3.4 INTRODUCTION

Home-grown feed consumption underpins the profitability of dairying in south-eastern (SE) Australia, as grazed pasture is the cheapest feed source available (Savage and Lewis 2005; Chapman *et al.* 2008a). Perennial ryegrass (*Lolium perenne* L.) is the main sown pasture species in SE Australian dairying regions (Jacobs and Woodward 2010). Advantages of perennial ryegrass include ease of establishment (Reed *et al.* 2008), high annual yield potential [>20 t dry matter (DM)/ha if irrigated], high feed quality (Garcia and Fulkerson 2005), grazing tolerance (Wilkins 1991), and responsiveness to nitrogen fertiliser (Pembleton *et al.* 2013); however, its disadvantages are strong seasonality in growth and nutritive value (Jacobs *et al.* 1999; Chapman *et al.* 2008a).

Cumulative summer yields (January-February) achieved by rain-fed perennial ryegrass pasture can be as low as 5-10% of annual production (Özkan *et al.* 2015). This can be explained by perennial ryegrass's sensitivity to the hot and dry summer conditions experienced in many SE Australian dairying regions (Mitchell 1956; Norris 1982; Rawnsley *et al.* 2007a). Summer conditions are projected to become even more challenging for perennial ryegrass-based pasture production in SE Australia (Harrison *et al.* 2016; Harrison *et al.* 2017).

The sensitivity of perennial ryegrass growth to dry conditions (i.e. soil water deficit) largely results from its shallow root system (Garwood and Sinclair 1979; Crush *et al.* 2005). Even when irrigated, the growth and persistence of perennial ryegrass are often challenged by supraoptimal ambient temperatures (T_a) (≥30˚C) (Arcioni *et al.* 1985; Neal *et al.* 2009). Supraoptimal temperature stress is particularly problematic for rain-fed pastures experiencing soil water deficit, as the combined stresses have a greater negative effect on plant growth and survival than either individual stress (i.e. they act synergistically) (Jiang and Huang 2000, 2001b). This is because soil water deficits constrain transpiration (Feldhake *et al.* 1984; Temple and Benoit 1988), which limits the ability of plants to avoid detrimental effects of supraoptimal temperature stress because transpiration can depress canopy temperature by >7˚C below T_a (i.e. transpirational cooling) (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004; Richardson 2004).

Summer feed deficits can potentially be alleviated by incorporating alternative summer-active temperate (C_3) perennial forages in the feed-base that are more tolerant of

hot and/or dry conditions than perennial ryegrass (Chapman *et al.* 2008b). Agronomically, we define tolerance as a species ability to grow during or shortly after cessation of stress. The effect of these conditions on key physiological processes can be used to assess tolerance. Photosynthesis is a key physiological process sensitive to supraoptimal temperature stress (Berry and Bjorkman 1980; Yordanov *et al.* 1986), with photosystem II (PSII) one of the most thermolabile aspects of photosynthesis (Santarius 1976; Havaux 1993; Havaux 1996).

Alternative summer-active temperate perennial forages worthy of investigation include (i) summer-active (continental-type) ecotypes of cocksfoot (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* Schreb.) and (ii) inherently summer-active species, including prairie grass (*Bromus catharticus* Vahl.), lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), chicory (*Cichorium intybus* L.), and narrow-leaf plantain (*Plantago lanceolata* L.). Many SE Australian studies have reported the potential of these species to out-yield perennial ryegrass pastures during summer, often without compromising annual production (Turner *et al.* 2006b, 2006a; Tharmaraj *et al.* 2008; Lawson *et al.* 2009; Clark *et al.* 2013; Ward *et al.* 2013; Tharmaraj *et al.* 2014).

Advantages of these summer-active temperate perennial forages for rain-fed systems include their capacity to avoid or delay the detrimental effects of soil water deficit (dehydration) (Volaire *et al.* 2009). Many of these species have deeper and more extensive root systems than perennial ryegrass (Wilman *et al.* 1998; Charlton and Stewart 1999; Ward *et al.* 2013), enabling them to avoid or delay dehydration by accessing stored soil water at greater depths (Farooq *et al.* 2009; Comas *et al.* 2013). These species are also summer-active, in that they can rapidly produce herbage after summer rainfall events (Lawson *et al.* 2007; Norton *et al.* 2008).

Cocksfoot and tall fescue are the only abovementioned species confirmed to be more resilient than perennial ryegrass to supraoptimal temperature stress (determined in growth chambers) (Mitchell 1956; Jiang and Huang 2001b). Anecdotal evidence for the superior tolerance of prairie grass to supraoptimal temperature stress is based on its ability to accumulate non-structural carbohydrate (NSC) reserves during spring. These reserves may support the elevated respiratory demands of plants exposed to supraoptimal temperature stress during summer (Fulkerson *et al.* 2000). Lucerne and red clover are presumed to be tolerant of supraoptimal temperature stress, as they can grow under irrigation in hot summer environments (e.g., where T_a regularly exceeds 40˚C) (Barnes and Sheaffer 1995; Al-

Ghumaiz 2012). Irrigated chicory growth is also resilient to high temperatures, being unaffected by increases in T_a from 20-30˚C (Lee *et al.* 2013). Plantain appears to be tolerant of supraoptimal temperature stress although most available evidence is anecdotal (Sagar and Harper 1964; Stewart 1996a).

This publication documents a glasshouse study testing the hypothesis that some of these species are more tolerant of supraoptimal temperature stress than perennial ryegrass. Supraoptimal temperature stress was imposed under both irrigated and non-irrigated conditions.

3.5 MATERIALS AND METHODS

3.5.1 Plant material

Nine summer-active temperate perennial forages were evaluated: two herbs, chicory cv. Grasslands Puna® and plantain cv. Ceres Tonic®; four grasses, perennial ryegrass cv. Grasslands Samson®, prairie grass cv. Ceres Atom®, cocksfoot cv. Megatas®, and tall fescue cv. Quantum II® MaxP™; and three legumes, birdsfoot trefoil (*Lotus corniculatus* L., Tas 2951), semi winter-dormant lucerne cv. SARDI Five®, and stoloniferous red clover cv. Rubitas®. Rhodes grass (*Chloris gayana* Kunth., cv. Katambora®) was included as a subtropical (C_4) grass reputed to be highly heat tolerant (Ivory and Whiteman 1978).

3.5.2 Growing conditions and establishment

Our study was undertaken in the glasshouse facility at the Tasmanian Institute of Agriculture, Burnie, Tasmania, Australia (41˚03'S, 145˚53'E; elevation 95 m). Both T_a and photoperiod were regulated by an environmental control system (Priva Maximiser; Priva Computers Inc., Vineland Station, ON, USA). A constant 14-15 h photoperiod was maintained using supplemental lighting; three 400 W halogen lamps and two dual 36 W fluorescent lamps per chamber (floor area 57 m^2). Canopy level photosynthetic active radiation (PAR), T_a, and relative humidity (RH) were recorded every 10 min by automated sensors and data loggers (HOBO micro station; Onset Computer Corporation, Bourne, MA, USA). Vapour pressure

deficit (VPD) was computed from T_a and RH, as outlined by Allen *et al.* (1998). During establishment, mean day/night T_a were 21/11˚C.

Plants were grown from seed in 3.8 L polyvinyl chloride pots (diameter 165 mm, height 240 mm), coloured white to minimise pot heating by direct solar radiation. On a volumetric basis, potting media consisted of 50% composted pine bark, 30% coarse sand, and 20% sphagnum peat. Potting media was fertilised with 2.20 kg/m^3 agricultural limestone, 2.00 kg/m^3 Osmocote® 8-9 Month Controlled Release Fertiliser (18% N, 4.8% P, and 8.3% K; Scotts Australia, Bella Vista, NSW, Australia), 1.60 kg/m^3 dolomite, 1.00 kg/m^3 blood and bone, 1.00 kg/m^3 single superphosphate, 0.50 kg/m^3 ferrous sulphate, and 0.34 kg/m^3 potassium sulphate.

During establishment, pots were arranged according to a randomised complete block design with four replicates. Pots were irrigated to through drainage every 1-3 days. After emergence, pots were thinned to 5 plants/pot. Legumes were inoculated 16 days after sowing (DAS), when all seedlings had attained the unifoliate leaf-stage. Birdsfoot trefoil, lucerne, and red clover were inoculated with *Mesorhizobium loti* (strain SU343), *Ensifer meliloti* (strain RRI128; group AL), and *Rhizobium leguminosarum* bv. *trifolii* (strain TAI; group B) respectively. During establishment, pot positions within blocks were regularly re-randomised.

Tiller and stolon development were encouraged by repeatedly defoliating plants to a 50 mm stubble height. Plants were defoliated at 54, 91, 127, 164, 199, 231, and 250 DAS. After each of the first four defoliations, 1.6 g/pot of Osmocote® Total All Purpose Controlled Release Fertiliser (20.9% N, 0.5% P, 3.8% K, and 8.8% S; Scotts Australia) was applied. This was increased to 3.2 g/pot for successive defoliations to encourage regrowth. At 107 DAS and after each of the final five defoliations, 0.6 g/pot of muriate of potash (50% K) and 0.2 g/pot of triple superphosphate (20.6% P and 1.5% S) were applied. At 111 and 178 DAS, 0.8 g/pot of Manutec® trace element granules (12.0% S, 10.0% Ca, 5.1% Fe, 5.1% Zn, 5.0% Mn, 2.9% Mg, 1.0% Cu, 0.5% B, and 0.006% Mo; Manutec, Cavan, SA, Australia) were applied

Plants were regularly sprayed with 20 mL/L of Yates® Pyrethrum Insecticide (16 g/L piperonyl butoxide, 4 g/L pyrethrins; Yates Australia, Padstow, NSW, Australia) to maintain aphid (Hemiptera: Aphididae) populations at non-damaging levels. Chambers were fogged

with 200 mL/L of Chlorpyrifos 500EC (500 g/L chlorpyrifos; Nufarm Australia, Laverton, Vic., Australia), 170 and 219 DAS. At the first appearance of rust (*Puccinia* spp.) on the Poaceae spp. (109 and 224 DAS), plants were sprayed with 3 mL/L of Yates® Copper Fungicide (93 g/L Cu; Yates Australia).

3.5.3 Experimental design and treatments

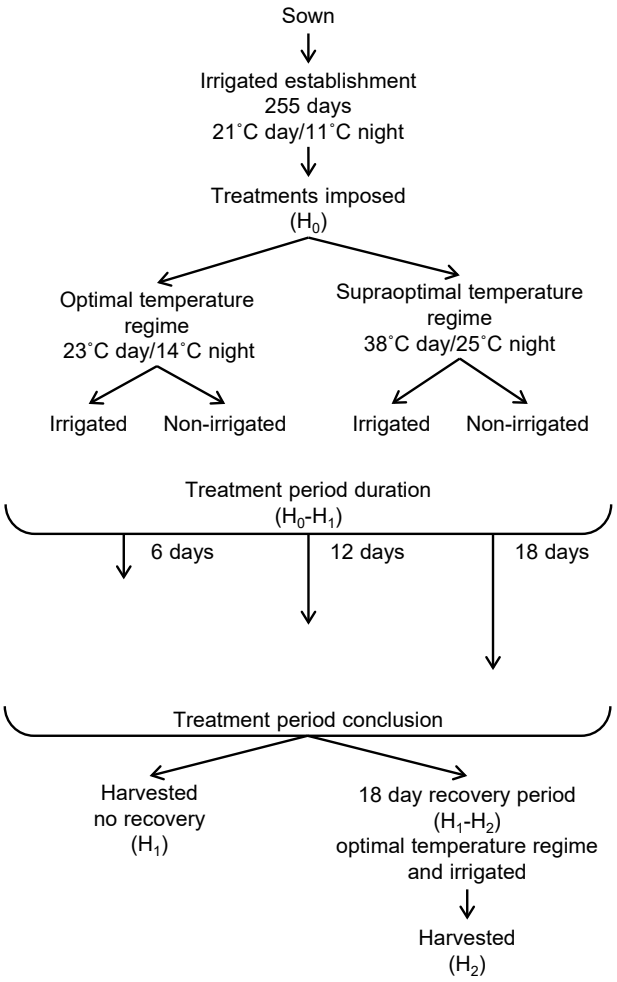

Figure 3.1 Schematic of the experimental sequence.

Treatments commenced at 256 DAS (H_0) and were imposed during January and February 2015. Pots were assigned to either an optimal (mean day/night T_a of 23/14˚C) or supraoptimal (mean day/night T_a of 38/25˚C) temperature regime. Temperature regimes were imposed in separate glasshouse chambers. Pots assigned to a temperature regime were

arranged according to a split-plot design that included four replicates arranged as blocks. Treatment period duration was the main-treatment, and all combinations of species, irrigation treatment, and recovery period were the subplot-treatments. There were 480 pots assigned to each temperature regime (four blocks by three treatment period durations by ten species by two irrigation treatments by two recovery periods). Pots were retained in their establishment blocks for the course of the experiment. Refer to Figure 3.1 for a schematic of the experimental sequence.

Irrigation treatments were either irrigated (daily to through drainage) or non-irrigated. At the commencement of treatments (H_0), potting media volumetric water content (θ_v) equalled 44 ± 0% (mean ± one standard error). The use of established plants and a limited root volume meant the rapid onset of water deficit stress occurred once irrigation ceased in the non-irrigated treatments. Abiotic stress treatments (temperature regime by irrigation treatment combinations) were maintained for 6, 12, or 18 days (treatment period durations H_0-H_1); i.e. double, quadruple, and sextuple respectively, the minimum number of consecutive days (3) constituting a SE Australian heat wave (Parker *et al.* 2014). Chamber effects were minimised by rotating pots assigned to a temperature regime between two chambers every 3 days. At the completion of a treatment period (H_1), pots were either (i) removed from the experiment, and plants were harvested (no recovery) or (ii) maintained under the optimal temperature regime and irrigated (daily to through drainage) for 18 days (recovery H_1-H_2). Plants subsequently recovered in chambers assigned to the optimal temperature regime and were rotated between two chambers every 3 days. During recovery, pots were retained in their original experimental/blocking structure, but rerandomised with respect to their position within their main-treatment. At the conclusion of recovery (H_2), pots were removed from the experiment and plants were harvested. Environmental conditions during the experiment are shown in Figure 3.2.

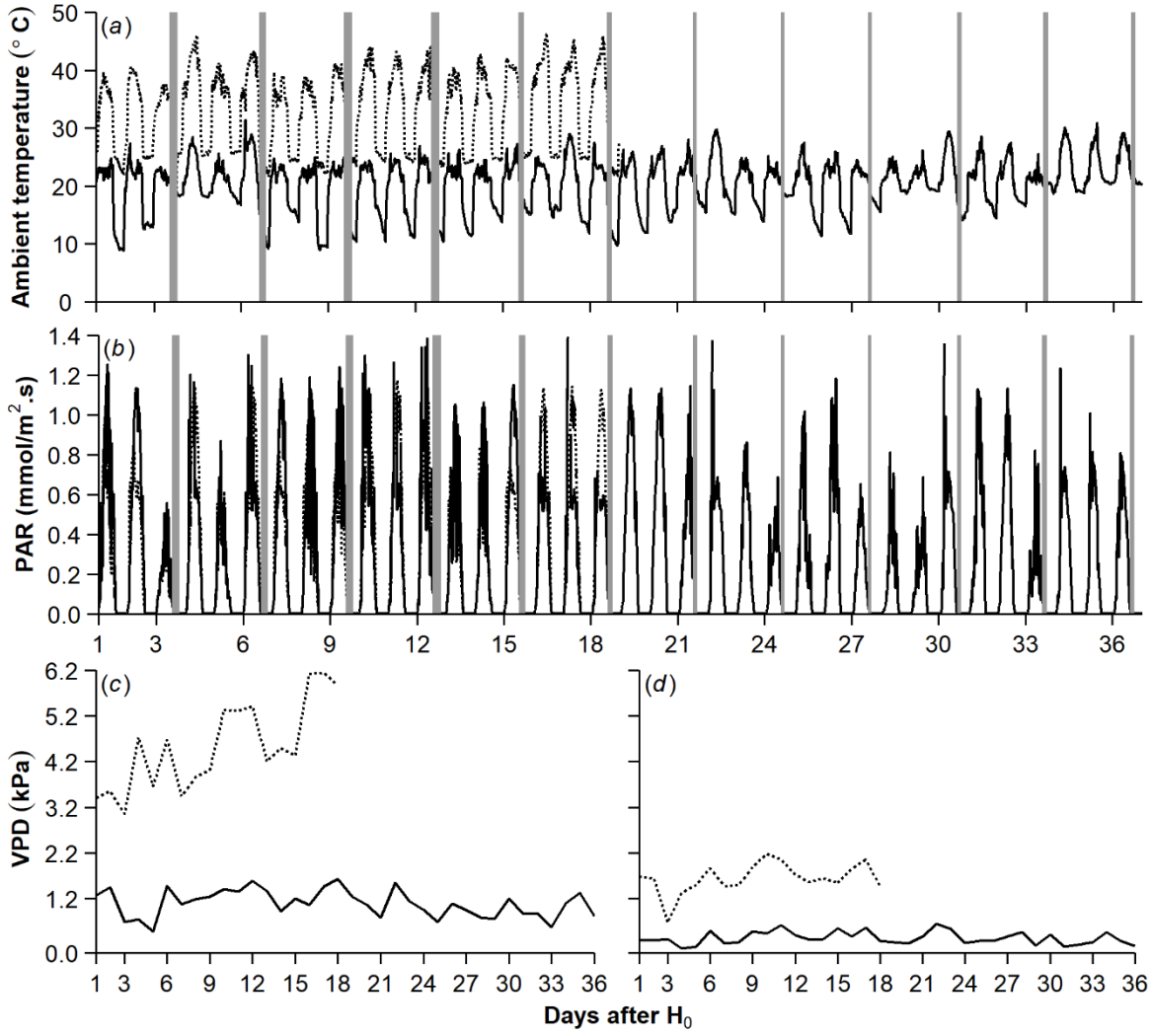

Figure 3.2 Glasshouse environmental conditions for optimal (——) and supraoptimal (▪ ▪ ▪ ▪) temperature regimes during the experimental period. Vertical bars (■) represent periods of chamber rotation. Environmental conditions are presented at 10 min resolution for canopy level (*a*) ambient temperature and (*b*) photosynthetically active radiation (PAR). Average daily canopy level vapour pressure deficit (VPD) values are also presented for the (*c*) day, and (*d*) night periods.

3.5.4 Harvest and measurements

Plants were harvested by collecting all herbage in each pot ≥50 mm above the potting media surface. Herbage was similarly collected during the final establishment defoliation, for use as a covariate. Harvested herbage was dried to constant weight at 60˚C in a forced-draught oven (Binder, Tuttlingen, Germany).

Leaf photochemical efficiency of PSII was estimated by measuring chlorophyll fluorescence (F_v/F_m) (Maxwell and Johnson 2000). Chlorophyll fluorescence was measured on dark-adapted plants using a pulse amplitude modulated fluorometer (OS-30p Chlorophyll Fluorometer, Opti-Sciences, Hudson, NH, USA). Plants in the 'no recovery' treatments were measured before harvest. Measurements were recorded over 48 h, with two blocks measured per night. Only the youngest fully-emerged leaves were measured, with the middle leaflet of legumes selected (avoiding the midrib).

Potting media θ_v was only monitored in pots assigned to both the '18-day treatment period duration' and 'recovery' groups. Sampling occurred every second day, ~14 h after irrigation concluded. Measurements were taken to a 70-mm depth using a frequency domain probe (Theta probe; Delta-T Devices Ltd., Cambridge, UK). Millivolt (mV) outputs were converted to θ_v with a potting media-specific calibration curve.

$$\theta_v = \frac{(1.07 + 6.4V - 6.4V^2 + 4.7V^3) - 0.8796}{7.2049}$$

3.5.5 Statistical analyses

For each temperature regime, H_1 yield and F_v/F_m data were analysed according to a split-plot design. Treatment period duration was the main-treatment, and combinations of species and irrigation treatment the subplot-treatments. Quantile-quantile plots of residuals were generated to assess data distributions, and the presence of heteroscedasticity. The F_v/F_m data were subsequently transformed to $(F_v/F_m)/(1-F_v/F_m)$ before analysis. Yield data from the final establishment defoliation were used as a covariate in yield analyses. Data were analysed using the PROC MIXED procedure in SAS 9.3 (SAS for Windows Release 9.3, SAS Institute, Cary, NC, USA). Least square means were calculated, with pairwise comparisons undertaken for all significant effects. Associated *P*-values were multiplicity-adjusted by simulation with PROC PLM (SAS 9.3) (Edwards and Berry 1987). Unless otherwise stated, differences discussed were significant at the $P<0.05$.

For each temperature regime, separate yield analyses were conducted for plants that had been non-irrigated for 6, 12, or 18 days using PROC MIXED (SAS 9.3). Both H_1 and H_2 yield data were included in each analysis. These data subsets were analysed assuming a randomised complete block design (fixed terms included species and recovery period). Quantile-quantile plots of residuals were generated to assess data distributions, and the

presence of heteroscedasticity; no transformations were required. Yield data from the final establishment defoliation were used as a covariate in the analyses. Because the species by recovery period interaction was always significant (P<0.05), partitioned analyses were used to compare H_1 and H_2 yields for each species.

Separate nonlinear models for irrigated and non-irrigated treatments were used to compare potting media θ_v curves. Models were developed with PROC NLIN and PROC NLMIXED (SAS 9.3). These included both treatment (0-18 days, H_0-H_1) and recovery (19-36 days, H_1-H_2) periods. The nonlinear model for the non-irrigated case was:

$$\theta_v = \begin{cases} a + b \cdot \exp(-c \cdot \text{day}), & \text{day} \leq 18 \\ d - e \cdot \exp[-f \cdot (\text{day} - 18)], & \text{day} > 18 \end{cases}$$

and the model for the irrigated case was:

$$\theta_v = a + b \cdot \exp(-c \cdot \text{day})$$

in which a is the minimum θ_v achieved upon conclusion of the treatment period (day 18, H_1), b is the difference between the initial θ_v (day 0, H_0) and a, parameter c controls the rate of θ_v decline during the treatment period (day 0-18, H_0-H_1), d is θ_v at the conclusion of recovery period (day 36, H_2), e is the extent of θ_v increase during the recovery period (day 19-36, H_1-H_2), and f controls the rate of θ_v increase during the recovery period (day 19-36, H_1-H_2). Further explanation for these parameters is provided in Figure 3.3.

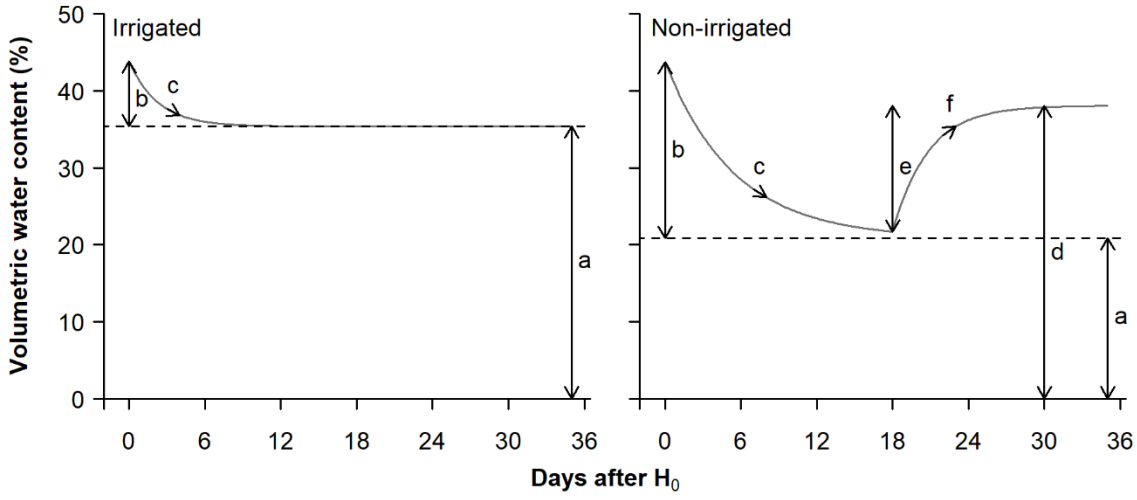

Figure 3.3 Nonlinear models (——) developed for potting media volumetric water content curves. The models include both treatment (day ≤18) and recovery (day >18) periods. Model parameters are described in text.

Nonlinear model parameters were used to compare potting media θ_v curves obtained under contrasting species for each temperature regime by irrigation treatment combination. Differences were established by comparing divergences from a reference level. Associated *P*-values were multiplicity-adjusted using the stepdown Sidak procedure for multiple comparisons (Westfall et al. 2011).

3.6 RESULTS

3.6.1 Volumetric water content (%)

The potting media θ_v of irrigated treatments declined from an initial level (H_0), before plateauing at the drained upper limit, indicating full watering (Figure 3.4).

The potting media θ_v of non-irrigated treatments declined over the 18 day treatment period, with the rate of decline subject to interspecies variation (Figure 3.4). Regardless of temperature regime, potting media θ_v declined at a greater rate in pots containing (i) perennial ryegrass relative to red clover and birdsfoot trefoil and (ii) cocksfoot, tall fescue, and plantain relative to birdsfoot trefoil. Interspecies variation in the extent and rate of potting media θ_v restoration during the recovery period (e.g. resumption of irrigation) was seldom significant (Figure 3.4).

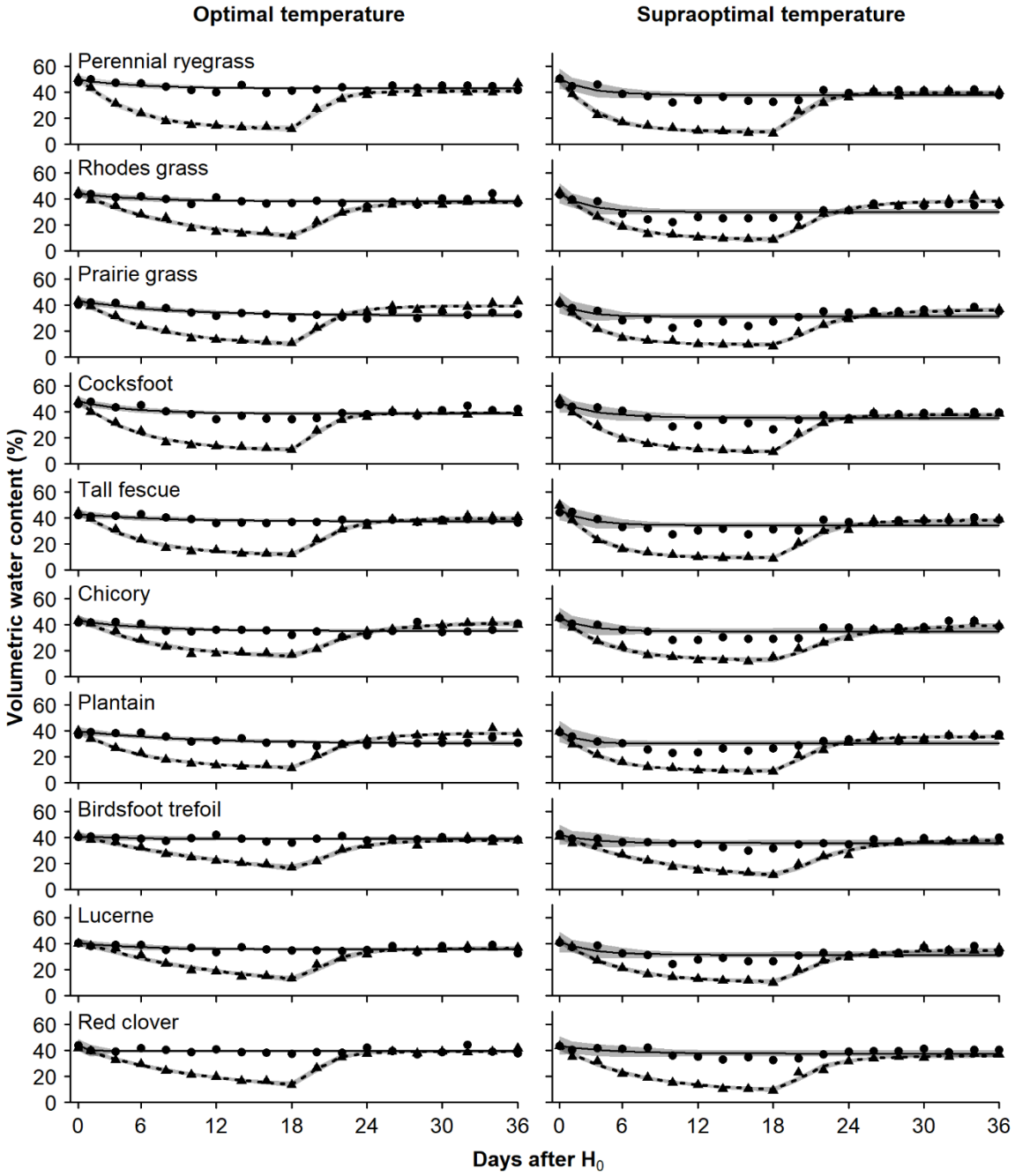

Figure 3.4 Nonlinear model fits for the potting media volumetric water content curves. Curves are shown for pots exposed to 18 days of contrasting temperature regimes and irrigation treatments, followed by an 18 day irrigated recovery period. Graphs show fitted mean curves for irrigated (——) and non-irrigated (▪ ▪ ▪ ▪) treatments, with 95% confidence interval bands for the predicted mean shown by grey shading (■). Mean observed data for irrigated (●) and non-irrigated (▲) treatments are also shown.

3.6.2 Dry matter yield

Irrigated plants continued growing after day 6 of the 18 day treatment period (i.e. DM yields were significantly higher after day 18 vs. 6 of the treatment period) (Figure 3.5). In contrast, non-irrigated plants ceased growth (i.e. DM yields after day 6, 12, or 18 of the treatment period did not significantly differ) (Figure 3.5).

Dry matter yields achieved in the supraoptimal vs. optimal temperature treatments could not be statistically compared, as temperature regimes were not replicated. With this important qualification, we still made observational comparisons between temperature regimes as they provided valuable insights. When irrigated, each temperate species had similar DM yields (H_1) after day 6 of the supraoptimal vs. optimal temperature regime (Figure 3.5). After 12 or 18 days of the supraoptimal temperature and irrigated treatment, DM yields (H_1) achieved by temperate species were often lower than yields achieved in the optimal temperature and irrigated treatment (Figure 3.5). In contrast, DM yields (H_1) of irrigated Rhodes grass were higher after 6, 12 or 18 days of the supraoptimal vs. optimal temperature regime. Cocksfoot, chicory, and birdsfoot trefoil were the temperate species least affected by 12 or 18 days of the supraoptimal temperature and irrigated treatment, achieving DM yields (H_1) >90% of those attained in the optimal temperature and irrigated treatment (Figure 3.5).

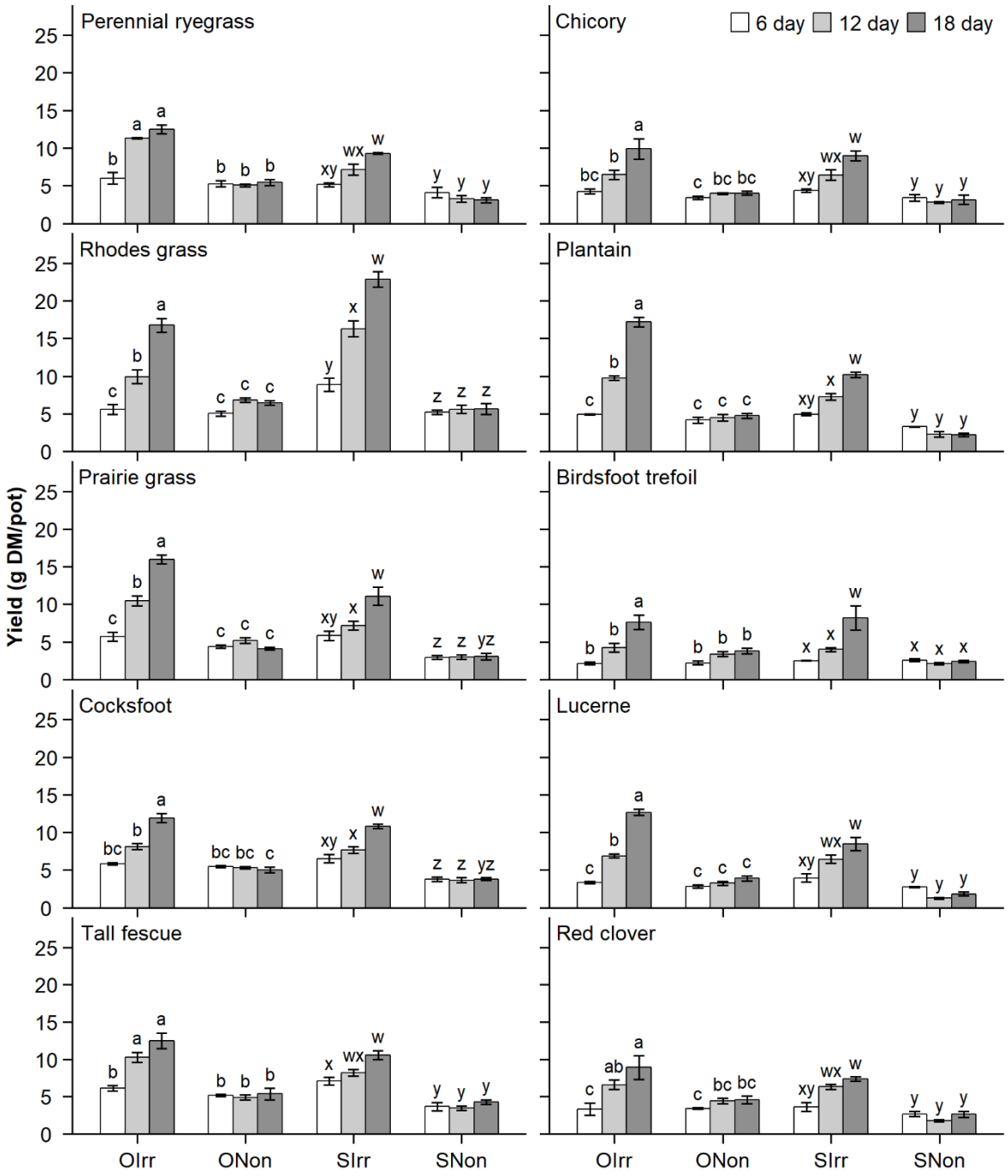

Figure 3.5 Interaction effects of treatment period duration by irrigation treatment by species on the dry matter (DM) yields achieved during the treatment period under the optimal or supraoptimal temperature regime. Abiotic treatments included: (i) optimal temperature and irrigated treatment, OIrr; (ii) optimal temperature and non-irrigated treatment, ONon; (iii) supraoptimal temperature and irrigated treatment, SIrr; and (iv) supraoptimal temperature and non-irrigated treatment, SNon. Treatment periods lasted 6, 12, or 18 days. Values are least square means ± one standard error of the mean. In each panel, values for each temperature regime annotated by the same letter are not significantly different ($P \geq 0.05$).

We assume recovery period growth occurred if DM yield attained at the end of the recovery period (H_2) significantly exceeded that attained at the end of the treatment period (H_1). All species grew in the recovery period following 6 or 12 days of the optimal temperature and non-irrigated treatment (Figure 3.6). After 18 days of this treatment, all species except plantain and red clover resumed growth in the recovery period.

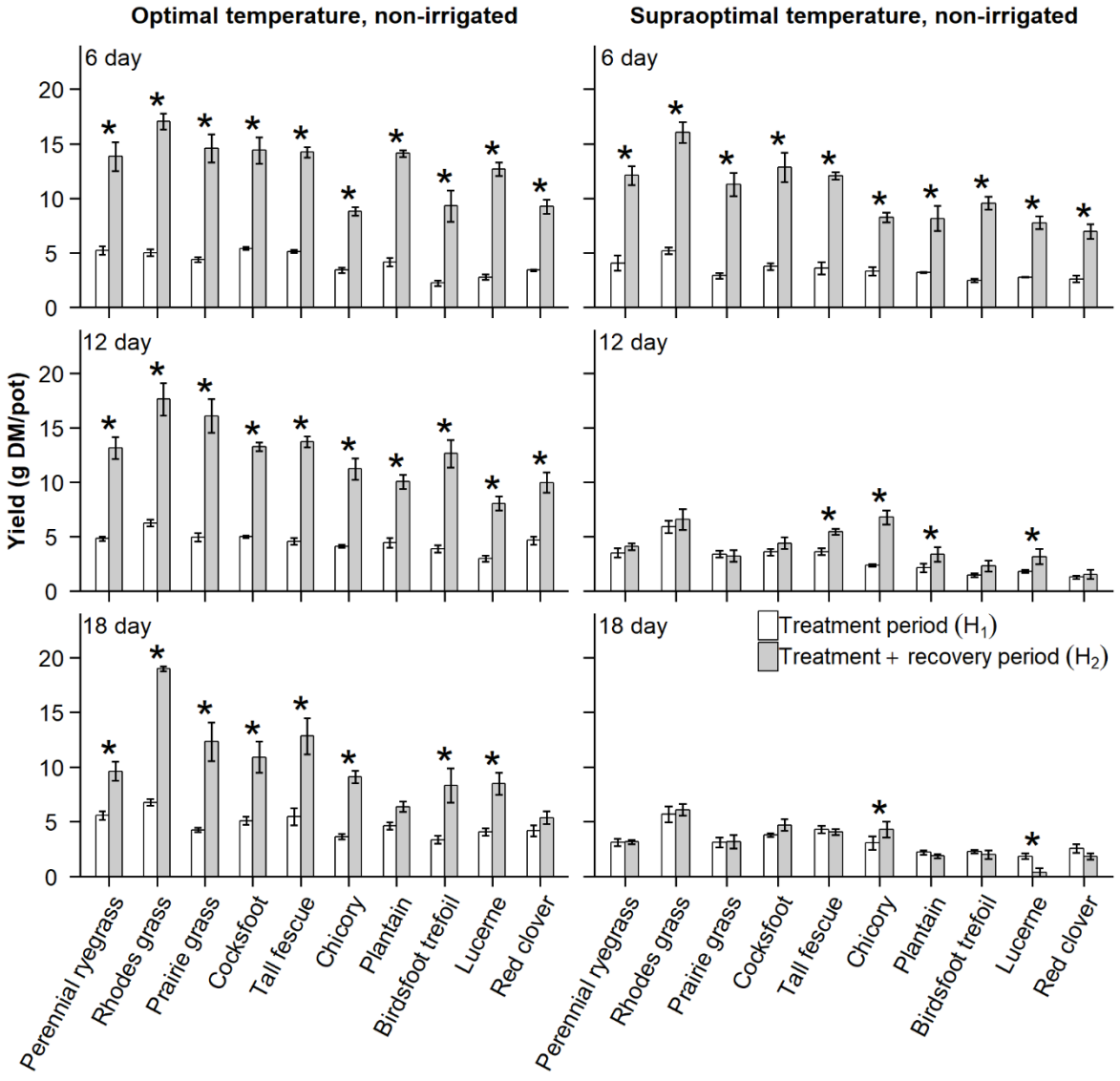

Figure 3.6 Interaction effects of species by recovery period on the dry matter (DM) yield of plants exposed to 6, 12, or 18 days of either the optimal or supraoptimal temperature regime and non-irrigation. Values are least square means ± one standard error of the mean. An asterisk (*) indicates a significant (P<0.05) difference existed between treatment (H_1) and treatment + recovery period (H_2) yields.

All species grew during the recovery period following 6 days of the supraoptimal temperature and non-irrigated treatment (Figure 3.6). After 12 days, only chicory, lucerne, plantain, and tall fescue resumed growth in the recovery period. Following 18 days, only chicory resumed growth in the recovery period. Chicory subsequently demonstrated a greater tolerance to the combination of stresses than all other examined forages (Figure 3.7).

Figure 3.7 Chicory (*a*-*c*) and perennial ryegrass (*d*-*f*) after 18 days of recovery from 6 (*a*, *d*), 12 (*b*, *e*), or 18 days (*c*, *f*) of the supraoptimal temperature and non-irrigated treatment.

3.6.3 Chlorophyll fluorescence ratio (F_v/F_m)

The F_v/F_m values for irrigated plants of each temperate species remained static throughout the 18 day treatment period (Figure 3.8).

Under the optimal temperature regime, F_v/F_m values for non-irrigated chicory, birdsfoot trefoil, lucerne and red clover plants remained static over the 18 day treatment period (Figure 3.8). By days 11-12 of the treatment period, F_v/F_m values for non-irrigated cocksfoot plants had diverged below irrigated levels (Figure 3.8). By days 17-18, F_v/F_m values for all grasses and plantain were lower in the non-irrigated vs. irrigated treatment (Figure 3.8).

Under the supraoptimal temperature regime, F_v/F_m values for non-irrigated birdsfoot trefoil plants remained static over the 18 day treatment period (Figure 3.8). Values for non-irrigated

chicory also declined little over this period (0.04 units). By days 11-12 of the treatment period, F_v/F_m values for all species with the exception of birdsfoot trefoil were lower in the non-irrigated vs. irrigated treatment (Figure 3.8).

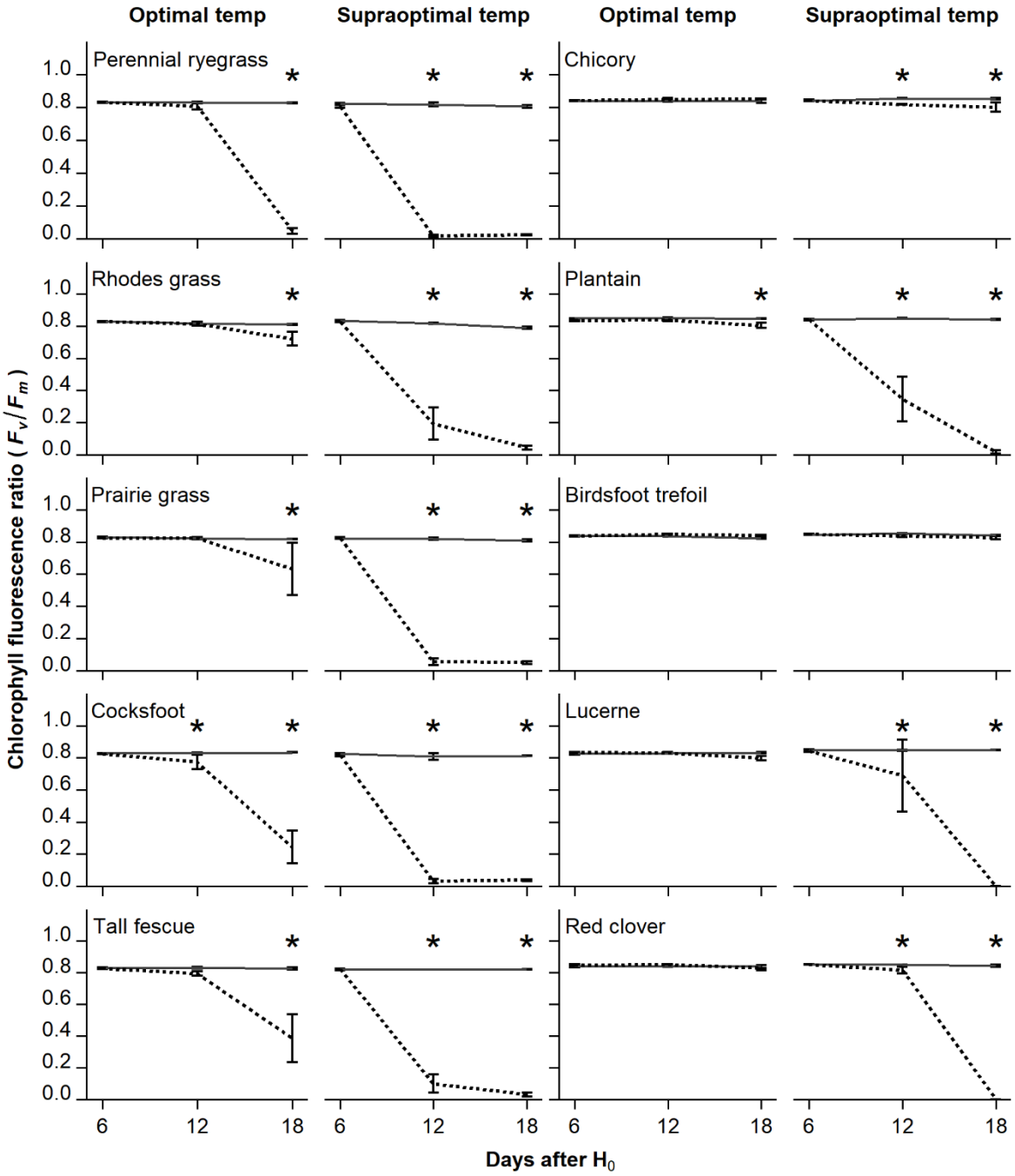

Figure 3.8 Interaction effects of treatment period duration by irrigation treatment by species on the chlorophyll fluorescence ratios (F_v/F_m) measured during the treatment period. Separate lines depict the two irrigation treatment levels: irrigated (——) and non-irrigated (▪ ▪ ▪ ▪). Values are back-transformed least square means ± one standard error of the mean. An asterisk (*) indicates a significant (P<0.05) difference existed between irrigated and non-irrigated treatments.

3.7 DISCUSSION

3.7.1 Chicory was the most tolerant of combined supraoptimal temperature and water deficit stress

Supraoptimal temperature stress combined with non-irrigation (i.e. water deficit) was more detrimental to plant growth and survival than either individual stress. Plants exposed to only supraoptimal temperature stress (supraoptimal temperature and irrigated treatment) continued growing after day 6 of the 18 day treatment period, whereas all non-irrigated plants ceased growth (Figure 3.5). Most species survived 18 days of the individual stress of non-irrigation (optimal temperature and non-irrigated treatment), as indicated by their growth during the recovery period. In comparison, few species survived 12 or 18 days of the combined stresses (Figure 3.6). The combined stresses had a more detrimental effect on F_v/F_m for most species than either individual stress. The F_v/F_m values for plants only exposed to supraoptimal temperature stress generally remained constant during the treatment period and were similar to values for unstressed plants (optimal temperature and irrigated treatment) (Figure 3.8). In comparison, F_v/F_m values for non-irrigated plants often declined below those receiving irrigation, with declines more common under the supraoptimal temperature regime. When F_v/F_m values declined under both temperature regimes, the decline occurred earlier and/or was of greater magnitude under the supraoptimal vs. optimal temperature regime (Figure 3.8). Our findings support previous research showing the combined stresses have greater detrimental effects on plants than either individual stress (Jiang and Huang 2000, 2001b). This is because water deficits constrain transpiration (Biran *et al.* 1981; Huang and Gao 1999) and the subsequent ability of plants to avoid supraoptimal temperature stress via transpirational cooling (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004). Therefore, we assume the severity of the combined stresses increased over the 18 day treatment period as θ_v progressively declined (Figure 3.4).

Chicory was the most tolerant of the combined stresses, being the only species to survive 18 days of this treatment (Figures 3.6 and 3.7). Of all species surviving 12 days of this treatment, chicory had the greatest capacity to resume growth during the recovery period, increasing in yield by 4.4 g DM/pot. This represented a 186% increase in yield above that determined at the end of the treatment period (Figure 3.6). In comparison, yield increases for other species surviving 12 days of the combined stresses were 74% (1.4 g DM/pot) for lucerne, 56% (1.2

g DM/pot) for plantain, and 51% (1.8 g DM/pot) for tall fescue (Figure 3.6). All other species did not survive 12 days of the combined stresses. Our study subsequently identified chicory and to a lesser extent lucerne, plantain, and tall fescue to be more tolerant than perennial ryegrass of supraoptimal temperature stress when combined with non-irrigation. This finding is supported by field observations of chicory, lucerne, and tall fescue having greater capacity than perennial ryegrass to grow after rainfall during hot and dry summers (Lawson *et al.* 2007; Nie *et al.* 2008; Raeside *et al.* 2014).

Chicory's tolerance for the combined stresses may be partly explained by retained leaves maintaining photosynthetic function (i.e. viable leaves) during the 18 day treatment period. This was evidenced by the F_v/F_m value of the youngest fully-emerged chicory leaves remaining at close proximity to the F_v/F_m range defined by Murchie and Lawson (2013) for non-stressed plants (0.81-0.83) (Figure 3.8). We assume these leaves assisted chicory plants in resuming growth during the recovery period by supplying photoassimilates for initial growth and plant repair. A similar mechanism may explain the ability of lucerne and plantain to resume growth after 12 days of the combined stresses. At days 11-12 of the combined stress treatment, F_v/F_m values for lucerne and plantain were 83% and 41% of those under unstressed conditions (Figure 3.8). These ratios exceeded that required (33%) for leaves of C_3 plants to recover from drought stress (Woo *et al.* 2008).

Ability of species to survive exposure to the combined stresses was not always indicated by the capacity to retain viable leaves during the treatment period. Birdsfoot trefoil did not survive either 12 or 18 days of the combined stresses, yet at the end of these treatment periods had leaves with F_v/F_m values of 0.83-0.85. Similar observations were made for red clover exposed to 12 days of the combined stresses (Figure 3.8). By day 12 of the treatment period, these species may have had insufficient remaining viable leaf area to supply the photoassimilates needed for growth to resume during the recovery period. Plants may have depended on these photoassimilates rather than their NSC reserves to resume growth. This is because the elevated respiratory demand of plants exposed to supraoptimal temperature stress can deplete the plants' NSC reserves (Sullivan and Sprague 1949; Alberda 1965; White 1973). Maintaining viable leaves during the treatment period would have further depleted plant NSC reserves (Wahid *et al.* 2007). In contrast to the dicots, tall fescue survived 12 days of the combined stress, despite exhibiting aboveground tissue senescence at days 11-12 of the treatment (F_v/F_m value, 0.1) (Figure 3.8). We assume tall fescue became

conditionally dormant during the treatment period (Vegis 1964; Norton *et al.* 2006b), and resumed growth in the recovery period by producing new leaves from its crown (Chai *et al.* 2010).

Our study does not provide definitive evidence to dismiss further examination of the other summer-active temperate perennial forages studied. The pot size used in our study (3.8 L) may have reduced the capacity of some of these species to avoid or delay dehydration via the development of deeper root systems (Farooq *et al.* 2009; Comas *et al.* 2013). Avoiding or delaying dehydration stress during periods of supraoptimal temperature stress is advantageous in reducing disruption to transpiration (i.e. transpirational cooling) (Jiang and Huang 2001b).

3.7.2 Irrigation mitigated the detrimental effect of supraoptimal temperature stress

Irrigation is widely used in SE Australian dairy systems, with forage production consuming 30% of total agricultural water in this region (ABS 2015). Our study highlights the potential role of irrigation in mitigating detrimental effects of supraoptimal temperature stress on examined species. Irrigation (daily to through drainage) enabled the temperate species to grow under supraoptimal temperatures. After 18 days, yields attained were 59-108% (mean 81%) of those under unstressed conditions (Figure 3.5).

Irrigated perennial ryegrass not only grew under the supraoptimal temperature regime, but after 18 days of this treatment still yielded 74% of that attained under unstressed conditions (Figure 3.5). This contrasts the well-cited (186 citations) research of Mitchell (1956), who found irrigated perennial ryegrass shoot growth rapidly declined when T_a >29˚C, with growth completely inhibited at 35˚C. We suggest plants in the study by Mitchell (1956) had a lower capacity to dissipate excess heat via transpiration, as the cooling effect of transpiration can be considerable (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004). Suggested differences in transpiration capacity are based on the lower VPD in the study by Mitchell (1956) (1.0 kPa at 29˚C, and 1.4 kPa at 35˚C). In comparison, the mean daytime VPD in our study was 4.5 kPa (range 3.1-6.1 kPa) (Figure 3.2c). It is conceivable that the lower VPD in the study by Mitchell (1956) may have limited transpiration, as transpiration rate is generally positively related to VPD (Forde *et al.* 1977; Hainaut *et al.*

2016). This positive relationship between VPD and transpiration rate is particularly evident at supraoptimal temperatures (Sermons *et al.* 2012; Sermons *et al.* 2017).

Due to the difficulty often associated with extrapolating results from glasshouse studies to field situations, the finding that irrigation mitigated the detrimental effects of supraoptimal temperature stress requires confirmation under field conditions. Such difficulty results from differences in the abiotic and biotic conditions experienced by plants (Ogunkunle and Beckett 1988; Passioura 2006; Wu *et al.* 2011; Poorter *et al.* 2016). Despite this, we have confidence in the applicability of the finding to field situations because the high daytime VPD levels maintained in our study (Figure 3.2c) approximated those experienced during SE Australian heat waves. Weather records from key Victorian dairying regions during the 2009 heat wave showed that on consecutive days when maximum T_a ≥35˚C, daily VPD ranged within 3.2-3.9 kPa in Ellinbank (Gippsland, SE Victoria), 2.3-4.2 kPa in Warrnambool (south-western Victoria), and 2.6-5.5 kPa in Kerang (northern Victoria). Confidence in the applicability of this finding to field situations is also provided by prior research indicating that shorter irrigation intervals increased the growth of temperate perennial forages during hot and dry summers (Greenwood *et al.* 2006). Depending on irrigation delivery system, it is not always possible to irrigate daily (as practiced in our study). Subsequently, there is a requirement for field-based research to quantify the effects of supraoptimal temperature stress on temperate species under more practical irrigation frequencies.

We observed interspecies variation in ability of irrigated plants to grow under the supraoptimal temperature regime. Cocksfoot, chicory, and birdsfoot trefoil were the temperate species most tolerant of individual supraoptimal temperature stress. Yields achieved by these species after 12 or 18 days of this treatment were always >90% of those under unstressed conditions (Figure 3.5). This observation supports previous research indicating cocksfoot to be more tolerant of irrigated supraoptimal temperature stress than perennial ryegrass (Mitchell 1956). Statistical confirmation and further explanation of these findings should be a focus of future research.

3.8 CONCLUSION

Our study showed chicory, and to a lesser extent lucerne, plantain, and tall fescue all possess tolerance to hot and dry conditions. These species may have a role to play in SE Australian dairy regions, where supraoptimal temperature stress is a frequent and ongoing issue. This requires confirmation under field conditions, due to the inherent difficulty in extrapolating findings from glasshouse pot studies to field situations. Our study found irrigation (daily to through drainage) mitigated the detrimental effect of supraoptimal temperature stress on all examined species. As irrigating on a daily basis can be impractical, there is a necessity for field-based research evaluating the potential of more practical irrigation frequencies to mitigate detrimental effects of supraoptimal temperature stress. Comprehensive field research in target environments is required, as the ability of irrigation to mitigate detrimental effects of supraoptimal temperature stress is dependent on a number of factors; e.g. soil texture, soil water retention curves, and irrigation delivery system. Further research on this topic will be presented in an accompanying publication.

Chapter 4: **Effect of stubble height management on crown temperature of perennial ryegrass, tall fescue and chicory**

4.1 OVERVIEW OF CHAPTER 4

Herbage removal via grazing or mechanical defoliation can result in the elevation of crown (plant-soil interface) temperatures, which can have detrimental effects on pasture species experiencing supraoptimal temperature stress. Research presented in Chapter 4 tests the hypotheses: (i) defoliating to shorter stubble heights (height of stubble above the surface) would elevate the upper distribution of crown temperatures (75th and 90th percentiles) experienced by perennial ryegrass (*Lolium perenne* L.), tall fescue (*Festuca arundinacea* Schreb.), and chicory (*Cichorium intybus* L.); and (ii) when defoliated to the same stubble height, upper distribution of crown temperatures for each of these species differs from each other. This experiment forms part of a larger study reported in Chapter 6.

Perennial ryegrass is included as it is the main pasture species sown in south-eastern Australian dairying regions (Chapman *et al.* 2006; Jacobs and Woodward 2010). Chicory was selected as the most tolerant of examined species to the combination of supraoptimal temperature and water deficit stress (Chapter 3). Of the three species possessing intermediate tolerance (lucerne, plantain, and tall fescue), tall fescue was identified as the most suitable candidate for inclusion into the current feed-base. An advantage of tall fescue compared to lucerne, is tall fescue's similar grazing management requirements to perennial ryegrass (Gramshaw *et al.* 1993; Raeside *et al.* 2012b, 2012a). Widespread adoption of lucerne in SE Australian dairying regions is potentially limited by ruminant health concerns (bloat) (Wang *et al.* 2012), and lucerne's known sensitivity to both aluminium toxicity (i.e. acidic soils) and waterlogging (Dear and Ewing 2008; Smith and Fennessy 2011). Tall fescue presents no ruminant health concerns when endophyte-free or infected with non-toxic endophytes (Parish *et al.* 2003), and possesses greater tolerance to aforementioned abiotic stresses (Rogers and Davies 1973; Scott *et al.* 2000; Ploschuk *et al.* 2017). Tall fescue was chosen over plantain because of the limited selection of herbicides available to manage weeds in swards containing plantain (Lockley and Wu 2008; Pembleton *et al.* 2015), and plantain monocultures being highly susceptible to weed incursion (Neal *et al.* 2009).

4.2 ABSTRACT

Defoliating pasture to shorter stubble heights (height of stubble above the soil surface) may increase temperature at the plant crown (plant-soil interface). A rain-fed field experiment in north-west Tasmania, Australia, quantified the effect of stubble height management on the upper distribution of crown temperatures (90th and 75th percentiles) experienced by three pasture species. Species examined included perennial ryegrass (*Lolium perenne* L.), tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort; syn. *L. arundinaceum* (Schreb.) Darbysh.], and chicory (*Cichorium intybus* L.). Three stubble height treatment levels were evaluated, *viz.* 35 mm, 55 mm, and 115 mm. Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the crown temperature of all species in the subsequent regrowth cycle (period between successive defoliation events). In the second summer, defoliating to shorter stubble heights increased the 90th percentile of crown temperature by an average of 4.2˚C for perennial ryegrass, 3.6˚C for tall fescue, and 1.8˚C for chicory. Chicory and second year tall fescue swards experienced less extreme crown temperatures than perennial ryegrass. This may partly explain the increasing interest in the use of these species to out-yield perennial ryegrass in hotter summer environments than north-west Tasmania.

4.3 KEYWORDS

Defoliation severity, grazing intensity, grazing management, leaf area index, mechanical defoliation, residual height

4.4 INTRODUCTION

In many south-eastern (SE) Australian dairying regions, summer pasture production can be constrained by above optimal (supraoptimal) ambient temperatures (T_a) (≥30˚C). This is due to the minimal supraoptimal temperature tolerance of the main sown pasture species, perennial ryegrass (*Lolium perenne* L.) (Mitchell 1956; Jacobs and Woodward 2010). Even with adequate irrigation, supraoptimal temperatures challenge perennial ryegrass growth and survival (Arcioni *et al.* 1985; Neal *et al.* 2009). Potential mitigation strategies pertain to both management, and incorporation of species more tolerant of supraoptimal temperature stress into the feed-base such as continental (summer-active) tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort; syn. *L. arundinaceum* (Schreb.) Darbysh.] and chicory (*Cichorium intybus* L.) [see Chapter 3 and Jiang and Huang (2001b)]. An added advantage of tall fescue and chicory is that they possess key attributes underpinning perennial ryegrass's popularity (Wilkins 1991); i.e. they are perennial (Rumball 1986; Raeside *et al.* 2012b), grazeable (Raeside *et al.* 2012a; Lee *et al.* 2015a), and of high nutritive value (Chapman *et al.* 2008b; Muir *et al.* 2015).

Defoliation management is one aspect of feed-base management requiring consideration, as defoliation can result in the elevation of plant crown (plant-soil interface) temperatures (Harrison *et al.* 2015). This is partly due to the reduced post-defoliation canopy leaf area index (LAI) permitting more solar radiation (SR) and sensible heat interception at the crown (i.e. direct radiation heat exchange). This mechanism has been confirmed in winter wheat (Harrison *et al.* 2015) and used to explain the amplification of soil temperature close to the surface (pedoderm): (i) following and during defoliation events (Bremer *et al.* 1998; Tanaka and Hashimoto 2006); and (ii) under fallow vs. pasture (Black and Aase 1988; Grant *et al.* 1995). In water-limited environments, greater SR interception at the canopy base may indirectly elevate crown temperature by reducing soil water content near the pedoderm (Black and Aase 1988; Matthew 1992; Liu *et al.* 2011). Reductions in soil water content can make soil surrounding the crown more susceptible to temperature increases (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015), while reducing the potential for evaporative cooling (Bremer *et al.* 2001).

Defoliation induced elevations in crown temperature, during periods of supraoptimal temperature stress, may negatively affect growth and survival of pasture species. This is due to the indeterminate meristematic tissue (apical meristem) responsible for phytomer

production being situated at the crown during vegetative growth (Rumball 1986; Korte *et al.* 1987; Yang *et al.* 1998). Phytomers are the basic repeating unit of vegetative growth, consisting of a leaf, internode, axillary bud, and one or more root primordia (Briske 1991; Gautier *et al.* 2001; Skinner and Moore 2007). Supraoptimal crown temperatures may reduce growth rates and challenge plant survival by: (i) impeding phytomer production via damage to the apical meristem (Mitchell and Lucanus 1962); (ii) damaging axillary bud development (Faust and Heins 1996; Schoellhorn *et al.* 2001), thereby limiting future tillering/shoot development (Mitchell 1956; Knievel and Smith 1973); and (iii) damaging existing axillary buds and root primordia (Dernoeden 2012).

Reducing the intensity of defoliation events (i.e. leaving a higher post-defoliation LAI) during hot summers may potentially limit plants' exposure to supraoptimal crown temperatures. In practice, defoliation intensity is more easily estimated by targeting a specific post-defoliation stubble height (height of stubble above the soil surface) than LAI (Rawnsley *et al.* 2014). This paper reports on a rain-fed field experiment established to test the hypothesis that defoliating to shorter stubble heights would elevate perennial ryegrass, tall fescue, and chicory crown temperatures. The experiment also tested the hypothesis that when defoliated to the same stubble height, interspecies crown temperature differences would exist. Confirmation of this hypothesis may assist in explaining the differential tolerance of these species to supraoptimal temperature stress.

4.5 MATERIALS AND METHODS

All data was collected from rain-fed (nil-irrigated) plots used in a larger study quantifying stubble height and irrigation management effects on the growth, botanical composition, and persistence of perennial ryegrass, tall fescue, and chicory swards (Chapter 6).

The experiment was conducted between September 2015 and April 2017 at the Tasmanian Institute of Agriculture Dairy Research Facility (41˚08'S, 145˚77'E; 155.0 m a.m.s.l), Elliott, north-west (NW) Tasmania, Australia. The location is characterised by a cool-temperate climate and winter-dominant rainfall pattern (mean annual rainfall, 1179 mm). The experimental site had minimal undulations, and a Red Mesotrophic Haplic Ferrosol soil (Isbell 1996). Additional site and soil details are provided in Chapter 6.

When considered in isolation, plots included in this experiment were arranged in a randomised complete block (RCB) design that included four replicates arranged as blocks. A total of 36 plots were included (four blocks by three pasture species by three stubble height treatments). Each plot measured 2 m by 3 m and was surrounded by a 0.5 m buffer of the selected pasture species.

On 17 September 2015, pasture species were sown into a fully prepared seedbed with an Oyjard small-plot drill (150 mm row spacing, 10 mm sowing depth). Tetraploid perennial ryegrass cv. Bealey® (NEA2, non-toxic endophyte), tall fescue cv. Quantum II® (MaxP®, non-toxic endophyte), and chicory cv. Puna® were sown at 25, 25, and 10 kg of uncoated seed/ha, respectively. Over 116 days, swards were established under spray irrigation and 300 mm of irrigation water was applied. Seventy-seven days after sowing (3 December 2015), swards were defoliated with a rotary lawnmower to a ~70 mm stubble height (Victa Mustang; Briggs and Stratton Corporation, Milwaukee, USA); cut herbage was removed, and no fertiliser applied. Detailed seedbed preparation and establishment descriptions are provided in Chapter 6.

On 7 January 2016 irrigation ceased (i.e. plots were rain-fed from this point onwards), and on 11-12 January 2016 swards were defoliated to their respective stubble height treatments (D_1). Swards were mechanically defoliated using a rotary lawnmower (SXG326; Iseki and Co., Ltd., Tokyo, Japan), with all cut herbage removed from plots. Cutting heights were set to leave a stubble height of either 35 mm, 55 mm, or 115 mm. Swards were defoliated to these stubble height treatments on twelve more occasions, denoted D_2 (9-10 February 2016), D_3 (15-16 March 2016), D_4 (27-28 April 2016), D_5 (21-22 June 2016), D_6 (23-24 August 2016), D_7 (12-14 October 2016), D_8 (9-10 November 2016), D_9 (9-10 December 2016), D_{10} (4-5 January 2017), D_{11} (1-2 February 2017), D_{12} (8-9 March 2017), and D_{13} (12-13 April 2017) (Figure 4.1). Scheduled defoliation events were based on the physiological status of irrigated perennial ryegrass (part of the larger study). Defoliation events occurred when the mean leaf regrowth stage of irrigated perennial ryegrass plants equalled 2.5 leaves/tiller. Defoliation events were occasionally scheduled at an earlier leaf regrowth stage (2.0 leaves/tiller) to prevent canopy closure or minimise reproductive development.

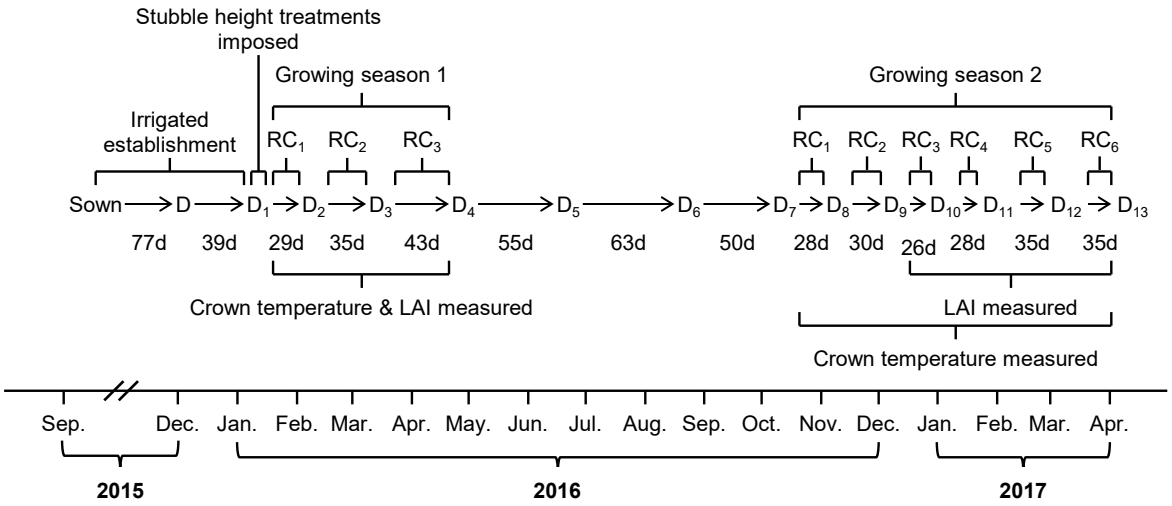

Figure 4.1 Schematic of the experimental sequence. Abbreviations include: (i) defoliation, D; (ii) regrowth cycle (RC), including regrowth cycles one to six (RC_1 to RC_6); and (iii) leaf area index, LAI.

Immediately following each defoliation event, 50 kg nitrogen (N)/ha (as urea, 46% N) was applied to prevent growth from becoming N limited. On 27 October and 25 November 2016, 80 kg muriate of potash/ha (50% potassium) and 511.4 kg single superphosphate/ha (8.8% phosphorus, 11% sulphur, and 19% calcium) was applied. Chlorpyrifos (0.9 L/ha of Apparent Dingo 500 at 0.45 kg active ingredient/ha; Apparent Pty Ltd, Hawthorn East, Australia) was sprayed once (15 February 2016) to control *Persectania ewingii* (Westwood) and *Teleogryllus commodus* (Walker).

During the experiment, ambient temperature and SR were logged at 5 min intervals by an on-site automatic weather station (Vantage Pro2; Davis® Instruments Corporation, California, USA). Crown temperature was monitored in three blocks (27 plots). In each plot, crown temperature was monitored via 2-3 self-contained, waterproof thermometers (DS1921G; Thermochron iButton Dallas Semiconductors, San Jose, CA, USA), with an accuracy of ±1˚C between -30˚C to 70˚C. Each thermometer was deployed ≥0.5 m inside the plot perimeter, and vertically inserted into the plant crown so that half (~8.7 mm) of the thermometer sat below the soil surface. Crown temperature was recorded during multiple regrowth cycles, within two growing seasons. Growing season one consisted of three regrowth cycles, including RC_1 (summer, D_1-D_2), RC_2 (summer, D_2-D_3), and RC_3 (autumn, D_3-D_4). Six regrowth cycles comprised growing season two, including RC_1 (spring, D_7-D_8), RC_2 (spring, D_8-D_9), RC_3 (summer, D_9-D_{10}), RC_4 (summer, D_{10}-D_{11}), RC_5 (summer, D_{11}-

D_{12}), and RC_6 (autumn, D_{12}-D_{13}) (Figure 4.1). On average, thermometers were deployed to start logging 3 days post-defoliation (range, 2-5 days), and removed 2 days before the subsequent defoliation event (range, 1-3 days). Crown temperature was logged at 30 min intervals.

Relative canopy LAI was measured using a non-destructive canopy analysis system (SunSCAN model SS1-R3-BF3; Delta-T Devices Ltd, Cambridge, UK). Absorption and ellipsoidal leaf angle distribution constants were set at 0.85 and 1.0, respectively. In each monitored regrowth cycle, canopy LAI was measured on four or more occasions. In growing season one, measurements were taken during RC_1 (15 January, 20 January, 1 February, and 8 February 2016), RC_2 (13 February, 21 February, 27 February, 6 March, and 12 March 2016), and RC_3 (19 March, 28 March, 4 April, 11 April, 20 April, and 25 April 2016) (Figure 4.1). In growing season two, measurements were only taken during the final four regrowth cycles. These included RC_3 (12 December, 20 December, 24 December 2016, and 2 January 2017), RC_4 (6 January, 12 January, 19 January, and 29 January 2017), RC_5 (3 February, 11 February, 18 February, 27 February, and 5 March 2017), and RC_6 (10 March, 18 March, 28 March, 5 April, and 10 April 2017) (Figure 4.1). At each measurement, overall canopy LAI of each plot was estimated by taking measurements at 0.6, 1.2, 1.8, and 2.4 m increments along the 3 m length of the plot. At each point, the SunSCAN probe was positioned 0.5 m into the plot and flush with the soil surface.

4.5.1 Statistical analyses

Crown temperature data was analysed separately for each growing season using quantile regression via the QUANTREG procedure in SAS 9.3 (SAS for Windows Release 9.3; SAS Institute, Cary, NC, USA) (Koenker 2005).

Prior to quantile regression, an autoregressive time series model of order two was fitted to the mean variable. Also included was: (i) a linear predictor, being Day of regrowth cycle, which removed linear changes; (ii) a quadratic trend Day^{-2}, which removed curvature; and (iii) cosine and sine terms based on the Day variable, which removed diurnal variation. The cosine and sine terms were defined as:

Day_2c = cos(2 x 3.14159 x Day),

Day_2s = sin(2 x 3.14159 x Day),

Day_4c = cos(4 x 3.14159 x Day),

Day_4s = sin(4 x 3.14159 x Day).

The autoregressive model was developed with PROC AUTOREG in SAS 9.3. Residuals obtained from the model for the time period, 0800-1700 h (Australian eastern standard time; universal time +1000), were used in the quantile regression to assess treatment effects. As this study was concerned with supraoptimal crown temperatures, analyses were restricted to the 75th and 90th percentiles (i.e. upper end of the crown temperature distribution). Quantile regression was used to model the proportion of time-series adjusted data that fell below the 75th and 90th percentiles. Non-significant terms were removed for the model. Associated *P*-values of pairwise comparisons were multiplicity-adjusted using simulation (Westfall *et al.* 2011). Unless otherwise stated, differences discussed were significant at the $P<0.05$ level.

Canopy LAI was analysed separately for each species by growing season by regrowth cycle combination. An RCB analysis of variance (ANOVA) was used within a repeated measures context to compare stubble height treatments for each species. The correlation structure of the repeated measures analysis was modelled using a one-dimensional spatial power function, which depended on the number of days since measurements commenced. Quantile-quantile plots of residuals were generated to assess data distributions, and the presence of heteroscedasticity; no transformations were required. Non-significant terms were removed from the model. Least square means were calculated, with pairwise comparisons undertaken for all significant effects. Associated *P*-values were adjusted using Tukey's adjustment for multiple comparisons. PROC MIXED and PROC PLM in SAS 9.3 were used for the analysis and post-hoc tests, respectively. Unless otherwise stated, differences discussed were significant at the $P<0.05$ level.

4.6 RESULTS

4.6.1 Weather conditions

In both growing seasons, mean maximum and minimum daily T_a were highest during summer regrowth cycles (Figure 4.2a). Summer regrowth cycles included: (i) growing season one, RC_1-RC_2; and (ii) growing season two, RC_3-RC_5. During the experiment, mean monthly maximum and minimum daily T_a deviated minimally (≤2.7˚C) from the long-term average (1975-2014) (Figure 4.2b). Mean monthly total daily SR also deviated minimally from the long-term average (≤2.3 MJ/m^2) (Figure 4.2c).

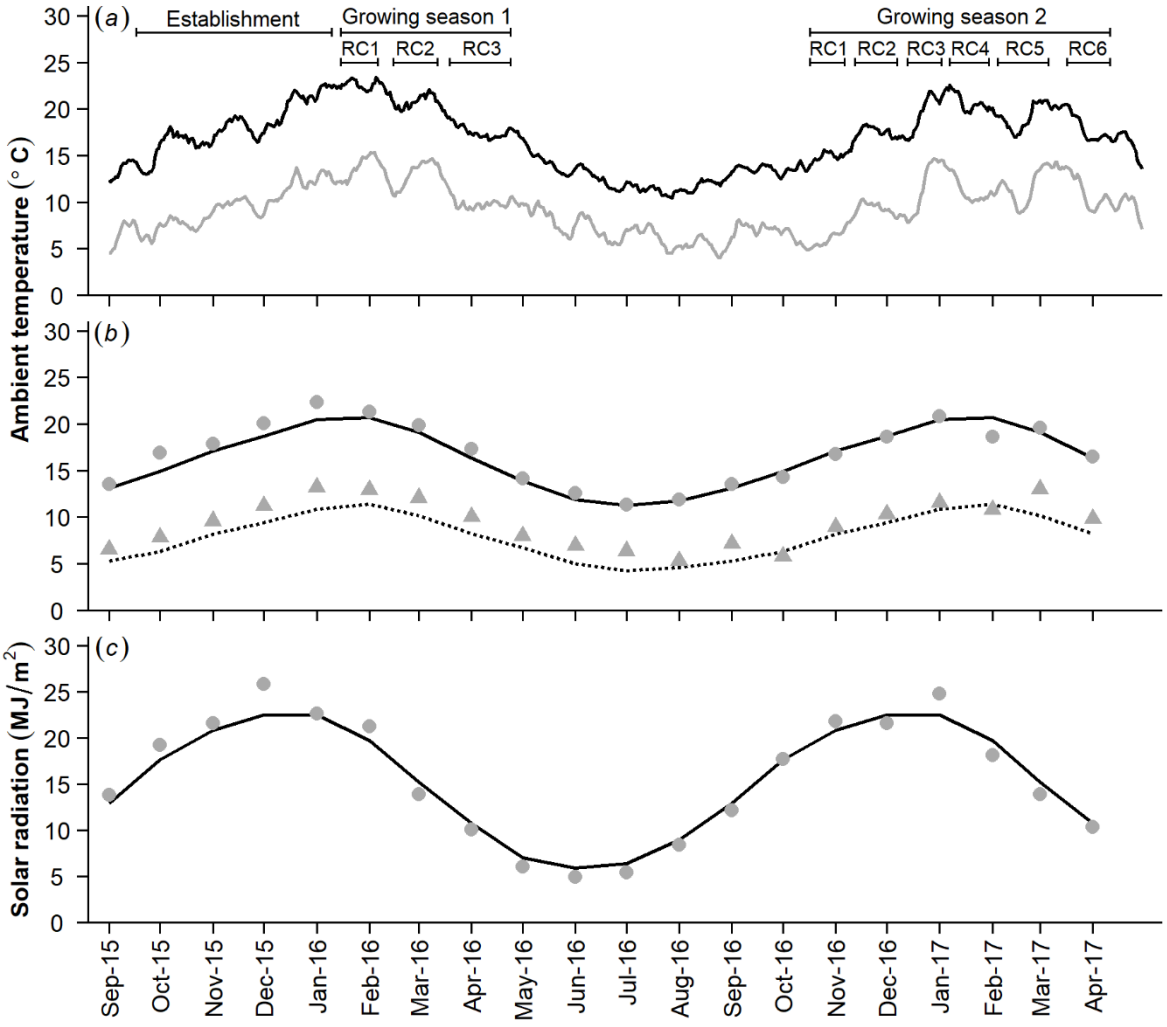

Figure 4.2 Eleven-day moving-average for maximum (——) and minimum (——) daily ambient temperature (*a*) during the experiment. Mean climatic data for each calendar month of the experiment (E) is presented with long-term (LT) means (1975-2014) for (*b*) maximum [E (●); LT (——)] and minimum [E (▲); LT (▪ ▪ ▪ ▪)] daily ambient temperatures, and (*c*) total daily solar radiation [E (●); LT (——)].

4.6.2 Crown temperature

During summer regrowth cycles, crown temperature was, at most, ≥30˚C for 4% of the time (44 hours) in growing season one (RC_1-RC_2), and 9% of the time (170 hours) in growing season two (RC_3-RC_5) (Figure 4.3). Crown temperature values ≥35˚C were only experienced by perennial ryegrass and tall fescue. In growing season two, perennial ryegrass crown temperature was ≥35˚C for 2% of the time, when defoliated to a stubble height of 35 mm (39 hours) or 55 mm (41 hours).

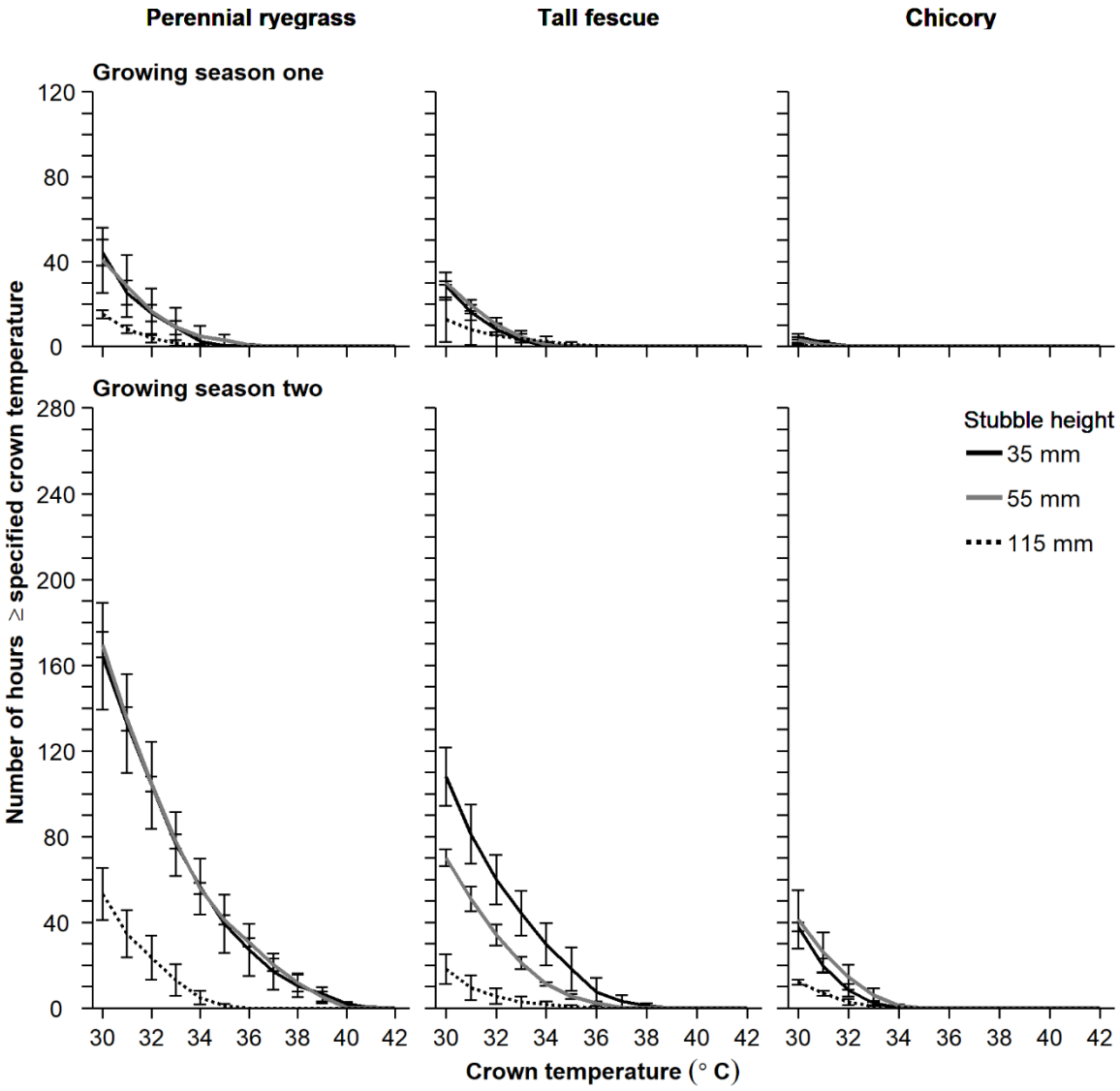

Figure 4.3 Number of logged summer hours when crown temperature was ≥30˚C. Crown temperature was logged over multiple regrowth cycles including RC_1-RC_2 for growing season one, and RC_3-RC_5 for growing season two. Crown temperature was logged for a total of 1200 hours (50 days) in growing season one, and 1824 hours (76 days) in growing season two. Values are means ± one standard error of the mean.

For crown temperature regression quantile analyses, significance levels for main-effects and interactions are shown in Table 4.1. Only the highest order significant (P<0.05) interactions are discussed.

Table 4.1 Significance levels for main-effects and interactions included in quantile regression analyses for the 75th and 90th percentiles of crown temperature. Each of two growing seasons (GS) were analysed separately. Wald tests for main-effects and interactions retained in refined models are presented. Abbreviations include: (i) degrees of freedom, DF; (ii) regrowth cycle, RC; (iii) species, S; and (iv) stubble height, SH.

			75th percentile		90th percentile	
GS	**Main-effect/interaction**	**DF**	**Chi-square value**	***P*-value**	**Chi-square value**	***P*-value**
1	SH	2	47.8	**	66.3	**
	S	2	4.1	NS	2.3	NS
	SH•S	4	12.8	*	26.6	**
	RC	2	445.8	**	179.9	**
	SH•RC	4			9.5	NS
	S•RC	4	68.6	**	19.4	**
	SH•S•RC	8			28.7	**
2	SH	2	17.8	**	10.4	**
	S	2	38.1	**	53.2	**
	SH•S	4	21.8	**	17.8	**
	RC	5	106.5	**	154.4	**
	SH•RC	10	63.2	**	91.5	**
	S•RC	10	107.0	**	112.5	**
	SH•S•RC	20	108.0	**	78.4	**

P-values, NS = non-significant (P≥0.05), *P<0.05, **P<0.01.

4.6.2.1 Growing season one

At the 75th percentile, crown temperature of each species under the 35 mm and 55 mm stubble height treatments did not differ significantly (stubble height by species interaction). At minimum, these values exceeded crown temperature under the 115 mm stubble height treatment by 1.8˚C for perennial ryegrass, 1.5˚C for tall fescue, and 0.7˚C for chicory (Tables 4.1 and 4.2). Observed stubble height effects on the 90th percentile of crown temperature differed across regrowth cycles (stubble height by species by regrowth cycle interaction) (Tables 4.1 and 4.3). In each regrowth cycle, tall fescue swards defoliated to stubble heights of 35 mm or 55 mm experienced 1.3-2.4˚C higher 90th percentiles of crown temperature than those defoliated to 115 mm. Defoliating to shorter stubble heights usually elevated

perennial ryegrass and chicory crown temperatures in both RC_2 and RC_3, but not RC_1. In RC_1, 90th percentiles of crown temperature for both species remained unaffected by stubble height treatment.

The 75th percentile of crown temperature significantly differed between species in both RC_1 and RC_2, but not RC_3 (species by regrowth cycle interaction) (Tables 4.1 and 4.2). In both RC_1 and RC_2, perennial ryegrass and tall fescue crown temperatures (75th percentile) did not significantly differ, but exceeded chicory crown temperature by an average of 2.2˚C. In each stubble height treatment, perennial ryegrass and tall fescue crown temperatures (75th percentile) did not significantly differ, but usually exceeded chicory crown temperature (stubble height by species interaction) (Tables 4.1 and 4.2). Only in the 115 mm stubble height treatment did tall fescue and chicory crown temperatures (75th percentile) not significantly differ from each other. In the 115 mm stubble height treatment, 90th percentiles of crown temperature did not significantly differ between species in any regrowth cycle (stubble height by species by regrowth cycle interaction) (Tables 4.1 and 4.3). In RC_1 and RC_2, 90th percentiles of crown temperature for perennial ryegrass seldom differed from tall fescue in the 35 mm and 55 mm stubble height treatments, but always exceeded chicory by ≥3.0˚C (stubble height by species by regrowth cycle interaction) (Tables 4.1 and 4.3). At the 90th percentile, crown temperatures for tall fescue and chicory in these stubble height treatments only differed in RC1, when tall fescue crown temperatures averaged 2.6˚C higher temperatures.

Table 4.2 Growing season one, 75th percentiles of crown temperature for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment and regrowth cycle (RC). Analysis was restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

Interaction			Perennial ryegrass		Tall fescue		Chicory	
SH•Species	SH (mm)	35	**24.3** (0.42 ± 0.06)	Aa	**23.8** (0.45 ± 0.14)	Aa	**22.0** (0.36 ± 0.13)	Ab
		55	**24.0** (0.44 ± 0.06)	Aa	**23.6** (0.42 ± 0.14)	Aa	**21.8** (0.35 ± 0.13)	Ab
		115	**22.2** (0.35 ± 0.03)	Ba	**22.1** (0.33 ± 0.09)	Bab	**21.1** (0.29 ± 0.08)	Bb
Species•RC	RC	1 (summer)	**27.8** (0.56 ± 0.06)	Aa	**27.1** (0.57 ± 0.15)	Aa	**24.9** (0.43 ± 0.14)	Ab
		2 (summer)	**24.3** (0.41 ± 0.05)	Ba	**24.1** (0.39 ± 0.13)	Ba	**22.3** (0.32 ± 0.13)	Bb
		3 (autumn)	**18.4** (0.24 ± 0.03)	Ca	**18.4** (0.24 ± 0.09)	Ca	**17.6** (0.24 ± 0.08)	Ca

Values followed by the same: (i) uppercase letter do not differ within a species (P≥0.05); and (ii) lowercase letter do not differ within a row (i.e. between species).

Table 4.3 For each regrowth cycle (RC) of growing season one, 90th percentiles of crown temperature are presented for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment. Analysis restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

RC	Season	SH (mm)	Perennial ryegrass		Tall fescue		Chicory	
1	summer	35	**30.8** (1.12 ± 0.11)	Aa	**29.5** (1.13 ± 0.09)	Aa	**27.5** (0.80 ± 0.06)	Ab
		55	**30.9** (1.05 ± 0.13)	Ab	**30.3** (1.28 ± 0.09)	Aa	**27.2** (0.82 ± 0.06)	Ac
		115	**28.7** (0.95 ± 0.09)	Aa	**27.9** (0.93 ± 0.10)	Ba	**26.2** (0.81 ± 0.05)	Aa
2	summer	35	**27.3** (0.90 ± 0.11)	Aa	**27.0** (0.89 ± 0.07)	Aab	**24.3** (0.77 ± 0.04)	Ab
		55	**27.0** (0.82 ± 0.04)	Aa	**26.0** (0.79 ± 0.06)	Aab	**23.8** (0.65 ± 0.09)	ABb
		115	**24.8** (0.65 ± 0.07)	Ba	**24.7** (0.65 ± 0.07)	Ba	**23.0** (0.56 ± 0.04)	Ba
3	autumn	35	**20.7** (0.49 ± 0.05)	ABb	**21.0** (0.64 ± 0.05)	Aa	**20.0** (0.65 ± 0.05)	Aa
		55	**20.5** (0.58 ± 0.04)	Aa	**20.3** (0.56 ± 0.05)	Aa	**19.5** (0.53 ± 0.04)	Ba
		115	**19.0** (0.39 ± 0.03)	Ba	**18.7** (0.39 ± 0.03)	Ba	**18.5** (0.42 ± 0.03)	Ca

Values followed by the same: (i) uppercase letter do not differ within a RC by species combination ($P \geq 0.05$); and (ii) lowercase letter do not differ within a row (i.e. between species).

4.6.2.2. Growing season two

In the second growing season, an interaction between stubble height by species by regrowth cycle was observed on the 75th and 90th percentiles of crown temperature (Tables 4.1, 4.4 and 4.5). In each regrowth cycle, perennial ryegrass crown temperature (75th and 90th percentiles) for the 35 mm and 55 mm stubble height treatments did not significantly differ, but usually exceeded crown temperature under the 115 mm stubble height treatment. Across summer regrowth cycles (RC_3-RC_5), crown temperature differences averaged 3.1˚C for the 75th percentile, and 4.2˚C for the 90th percentile. In each regrowth cycle, tall fescue crown temperatures (75th and 90th percentiles) were usually higher under the 35 mm or 55 mm cf. 115 mm stubble height treatment. Tall fescue crown temperature (75th and 90th percentiles) was either equal or greater under the 35 mm compared to the 55 mm stubble height treatment. At the 75th percentile, chicory crown temperature was observed to be affected by stubble height in RC_1, RC_3 and RC_5. In each of these regrowth cycles, chicory crown temperature under the 35 mm and 55 mm stubble height treatments were not significantly different, but exceeded crown temperature under the 115 mm treatment by 1.2-1.5˚C. Similar observations are made in RC_1-RC_4 for the 90th percentile of chicory crown temperature, with differences ranging between 1.3-2.5˚C. In both RC_5 and RC_6, chicory crown temperature (90th percentile) significantly differed between the 55 mm and 115 mm stubble height treatments, averaging 1.5˚C higher under the 55 mm stubble height treatment.

In each stubble height treatment, perennial ryegrass crown temperatures (75th and 90th percentiles) in most regrowth cycles equaled or exceeded tall fescue crown temperatures, and mostly exceeded chicory crown temperatures. In both the 35 mm and 55 mm stubble height treatments, tall fescue experienced higher crown temperatures than chicory in more regrowth cycles when comparisons are made at the 90th vs. 75th percentile. At the 90th percentile of crown temperature, tall fescue exceeded chicory by (i) 2.5-7.6˚C across RC_1-RC_5, 35 mm stubble height treatment; and (ii) 1.8-5.0˚C across RC_1-RC_3 and RC_5, 55 mm stubble height treatment. In the 115 mm stubble height treatment, 75th and 90th percentiles of tall fescue crown temperature exceeded chicory in RC_1 by 4.3˚C and 5.2˚C, respectively. In all other regrowth cycles, crown temperature of these two species seldom differed from each other.

Table 4.4 For each regrowth cycle (RC) of growing season two, 75th percentiles of crown temperature are presented for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment. Analysis restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

RC	Season	SH (mm)	Perennial ryegrass		Tall fescue		Chicory	
1	spring	35	**21.7** (0.60 ± 0.05)	Aa	**22.3** (0.60 ± 0.09)	Aa	**17.0** (0.30 ± 0.03)	Ab
		55	**21.7** (0.59 ± 0.05)	Aa	**20.8** (0.49 ± 0.08)	ABa	**16.8** (0.24 ± 0.03)	Ab
		115	**19.5** (0.35 ± 0.05)	Ba	**19.8** (0.38 ± 0.04)	Ba	**15.5** (0.14 ± 0.03)	Bb
2	spring	35	**26.5** (0.70 ± 0.04)	Aa	**27.1** (0.78 ± 0.06)	Aa	**20.8** (0.31 ± 0.04)	Ab
		55	**25.3** (0.63 ± 0.07)	Aa	**22.8** (0.35 ± 0.04)	Bb	**20.3** (0.29 ± 0.03)	Ab
		115	**23.8** (0.37 ± 0.04)	Ba	**21.0** (0.24 ± 0.04)	Cb	**19.0** (0.22 ± 0.05)	Ab
3	summer	35	**28.5** (0.74 ± 0.09)	Aa	**26.8** (0.54 ± 0.08)	Ab	**23.5** (0.45 ± 0.04)	Ab
		55	**28.8** (0.72 ± 0.07)	Aa	**25.3** (0.48 ± 0.07)	Ab	**23.5** (0.44 ± 0.04)	Ab
		115	**26.2** (0.47 ± 0.06)	Ba	**23.5** (0.35 ± 0.03)	Bab	**22.3** (0.33 ± 0.03)	Bb
4	summer	35	**30.3** (0.77 ± 0.05)	Aa	**28.2** (0.64 ± 0.05)	Ab	**24.4** (0.42 ± 0.03)	Ac
		55	**30.2** (0.74 ± 0.06)	Aa	**26.7** (0.46 ± 0.05)	Bb	**24.9** (0.43 ± 0.04)	Ab
		115	**26.8** (0.45 ± 0.04)	Ba	**24.8** (0.33 ± 0.06)	Bb	**24.0** (0.36 ± 0.04)	Ab
5	summer	35	**28.2** (0.87 ± 0.07)	Aa	**27.2** (0.81 ± 0.06)	Aab	**25.0** (0.70 ± 0.04)	Ab
		55	**28.7** (0.96 ± 0.10)	Aa	**26.2** (0.81 ± 0.05)	Aab	**25.0** (0.71 ± 0.05)	Ab
		115	**25.0** (0.61 ± 0.04)	Ba	**23.8** (0.57 ± 0.07)	Ba	**23.7** (0.56 ± 0.06)	Ba
6	autumn	35	**23.9** (0.45 ± 0.05)	Aa	**23.0** (0.36 ± 0.03)	Aab	**21.7** (0.30 ± 0.03)	Ab
		55	**23.3** (0.37 ± 0.04)	ABa	**22.7** (0.32 ± 0.03)	Aa	**22.2** (0.32 ± 0.03)	Aa
		115	**22.8** (0.33 ± 0.03)	Ba	**21.0** (0.19 ± 0.03)	Bb	**21.5** (0.27 ± 0.03)	Aa

Values followed by the same: (i) uppercase letter do not differ within a RC by species combination ($P \geq 0.05$); and (ii) lowercase letter do not differ within a row (i.e. between species).

Table 4.5 For each regrowth cycle (RC) of growing season two, 90th percentiles of crown temperature are presented for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment. Analysis restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time series adjusted values should only be used for statistical comparisons.

RC	Season	SH (mm)	Perennial ryegrass		Tall fescue		Chicory	
1	spring	35	**24.5** (1.15 ± 0.10)	Aa	**25.4** (1.27 ± 0.11)	Aa	**18.7** (0.69 ± 0.06)	Ab
		55	**24.7** (1.13 ± 0.09)	Aa	**23.3** (1.05 ± 0.10)	Aa	**18.3** (0.52 ± 0.06)	Bb
		115	**21.5** (0.76 ± 0.03)	Ba	**22.0** (0.79 ± 0.07)	Ba	**16.8** (0.37 ± 0.05)	Cb
2	spring	35	**29.5** (1.27 ± 0.08)	Ab	**30.8** (1.60 ± 0.23)	Aa	**23.2** (0.75 ± 0.07)	Ac
		55	**28.3** (1.20 ± 0.08)	Aa	**25.1** (0.85 ± 0.03)	Bb	**22.2** (0.69 ± 0.06)	Ac
		115	**26.2** (0.85 ± 0.08)	Ba	**22.8** (0.59 ± 0.06)	Cb	**20.7** (0.48 ± 0.07)	Bb
3	summer	35	**33.4** (1.36 ± 0.06)	Aa	**31.5** (1.20 ± 0.10)	Aa	**26.5** (0.91 ± 0.05)	Ab
		55	**33.4** (1.32 ± 0.12)	Aa	**29.4** (1.11 ± 0.12)	Aa	**26.7** (0.87 ± 0.06)	Ab
		115	**29.5** (0.91 ± 0.07)	Ba	**26.5** (0.68 ± 0.06)	Bb	**25.2** (0.66 ± 0.09)	Bb
4	summer	35	**34.1** (1.24 ± 0.04)	Aa	**31.3** (1.14 ± 0.17)	Aa	**28.8** (0.79 ± 0.05)	Ab
		55	**33.4** (1.26 ± 0.05)	Aa	**29.3** (0.85 ± 0.07)	Bb	**28.5** (0.81 ± 0.07)	Ab
		115	**29.2** (0.79 ± 0.03)	Ba	**27.0** (0.66 ± 0.06)	Cab	**26.3** (0.63 ± 0.03)	Bb
5	summer	35	**32.0** (1.69 ± 0.06)	Aa	**30.8** (1.56 ± 0.19)	Aa	**28.3** (1.24 ± 0.07)	ABb
		55	**32.3** (1.76 ± 0.12)	Aa	**30.5** (1.55 ± 0.12)	Aa	**28.7** (1.30 ± 0.05)	Ab
		115	**28.0** (1.18 ± 0.07)	Ba	**27.2** (1.05 ± 0.15)	Ba	**27.0** (1.09 ± 0.14)	Ba
6	autumn	35	**27.4** (0.92 ± 0.10)	Aa	**26.1** (0.79 ± 0.06)	Aab	**24.7** (0.67 ± 0.06)	ABb
		55	**26.3** (0.81 ± 0.04)	ABa	**25.5** (0.66 ± 0.04)	Bb	**25.0** (0.70 ± 0.03)	Aab
		115	**25.3** (0.74 ± 0.05)	Ba	**23.2** (0.50 ± 0.04)	Cb	**23.7** (0.57 ± 0.04)	Bb

Values followed by the same: (i) uppercase letter do not differ within a RC by species combination ($P \geq 0.05$); and (ii) lowercase letter do not differ within a row (i.e. between species).

4.6.3 Canopy leaf area index

Within each regrowth cycle, canopy LAI values for each species were always significantly lower under the 35 mm or 55 mm cf. 115 mm stubble height treatment (Figure 4.4). In some regrowth cycles, canopy LAI values for both perennial ryegrass and tall fescue were significantly lower under the 35 mm vs. 55 mm stubble height treatment (Figure 4.4).

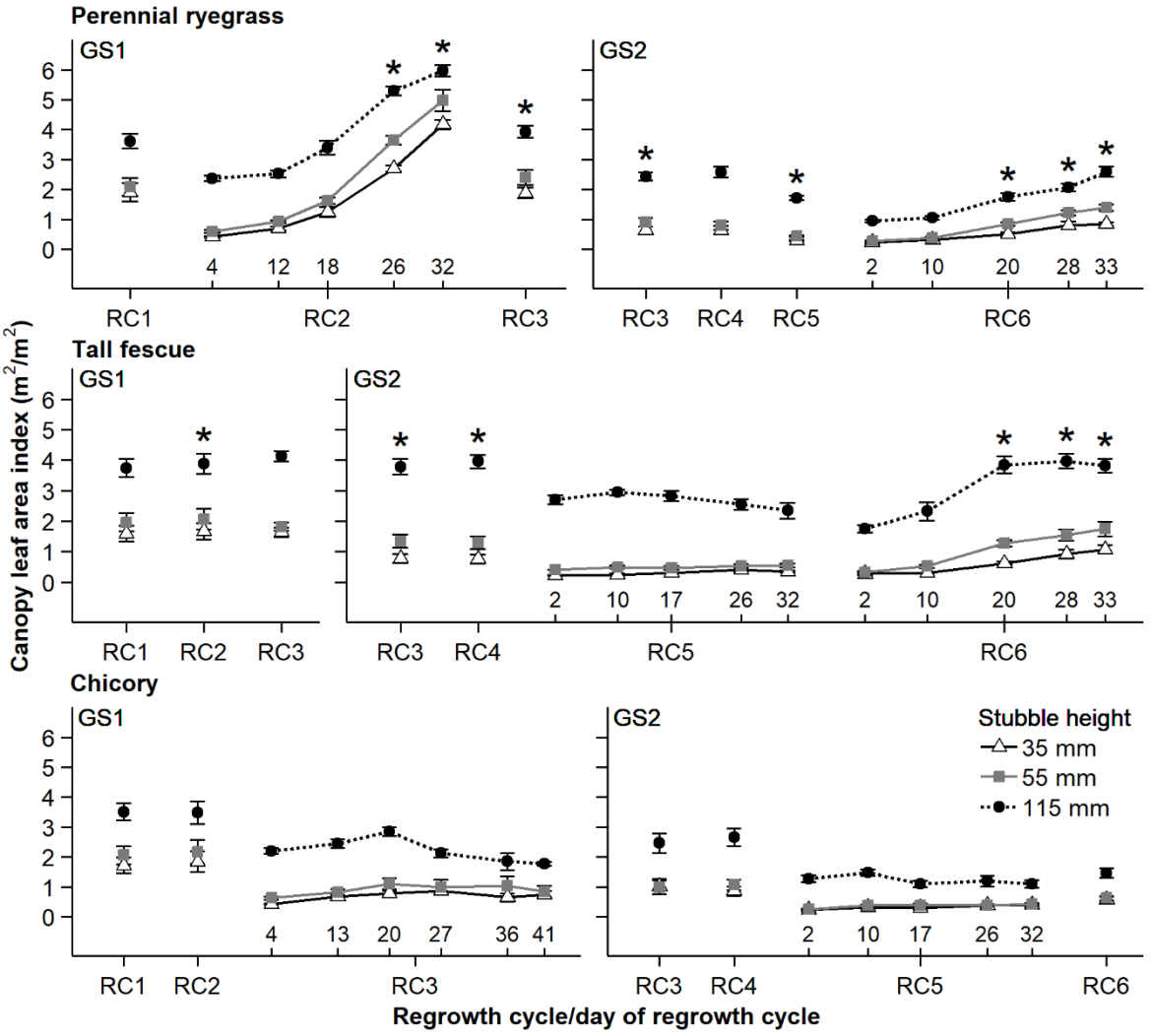

Figure 4.4 Relative canopy leaf area index (LAI) of perennial ryegrass, tall fescue, and chicory swards in each stubble height treatment. Growing season one (GS1) and two (GS2) are graphed separately. Regrowth cycles (RC) where: (i) stubble height was only significant (P<0.05) as a main-effect feature a single point for each stubble height treatment; and (ii) stubble height by measurement time interaction was significant are shown as a line series, with a point for each measurement time. Values are least square means ± one standard error of the mean. Swards defoliated to stubble heights of 35 mm or 55 mm always had significantly lower canopy LAI values than those defoliated to a 115 mm stubble height. An asterisk (*) signifies canopy LAI values were significantly lower under the 35 mm vs. 55 mm stubble height treatment.

4.7 DISCUSSION

4.7.1 Stubble height effects

Results demonstrate the potential of stubble height management to affect the crown temperature of three perennial pasture species. Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the likelihood of perennial ryegrass, tall fescue, and chicory experiencing higher crown temperatures in the subsequent regrowth cycle (Tables 4.2-4.5). As our study was concerned with supraoptimal crown temperatures only temperature increases at the upper end of the crown temperature distribution (75th and/or 90th percentiles) are reported. Across summer regrowth cycles of growing season two, defoliating to shorter stubble heights increased the 90th percentile of crown temperature by an average of 4.2˚C for perennial ryegrass, 3.6˚C for tall fescue, and 1.8˚C for chicory (Table 4.5). Observed crown temperature increases may be partially explained by the lower canopy LAI of swards defoliated to shorter stubble heights (Figure 4.4), which we assume permitted more SR interception at the canopy base (Harrison *et al.* 2015). Defoliating to lower stubble heights can also reduce the capacity of plants to dissipate excess heat via transpiration (Harrison *et al.* 2011), with the potential cooling effect of transpiration being considerable (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004).

The upper distribution of perennial ryegrass and chicory crown temperatures (75th and 90th percentiles) seldom differed between swards defoliated to stubble heights of 35 mm vs. 55 mm (Tables 4.2-4.5). We assume defoliating to these contrasting stubble heights did not unduly affect SR interception at the canopy base of either species, or their transpiration capacity. By contrast, tall fescue defoliated to a stubble height of 35 mm vs. 55 mm had increased crown temperatures in half the regrowth cycles of growing season two. Crown temperature increases were evident at both the 75th and 90th percentiles, which were elevated by as much as 4.3˚C and 5.7˚C, respectively (Tables 4.4 and 4.5). Tall fescue swards defoliated to stubble heights of 35 mm vs. 55 mm often had lower canopy LAI values (when measured, see Figure 4.4). While small in magnitude, these differences may have sufficiently affected levels of SR intercepted at the base of the tall fescue canopy to affect crown temperature.

Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the summer-autumn growth of each species (see Chapter 6). This result indicates supraoptimal crown

temperatures either did not occur, or occurred for insufficient duration to have detrimentally affected potential growth (Chen *et al.* 1982). We can confirm perennial ryegrass experienced periods of supraoptimal crown temperatures during summer regrowth cycles (>32˚C), even when defoliated to the 115 mm stubble height (Figure 4.3). This supraoptimal threshold is derived from previous research, which manipulated temperature of the stem apex (location of shoot apex, apical meristem, and growing points) at the crown (Peacock 1975b, 1975a). Stem apex temperatures >32˚C reduced the rate of perennial ryegrass leaf extension, which became negligible when stem apex temperatures reached 40˚C (Peacock 1975b). When defoliated to stubble heights of 35 mm or 55 mm, perennial ryegrass summer crown temperatures in growing season two exceeded this threshold, being ≥35˚C for 2% of the total time, and on a few occasions reaching ~40˚C (Figure 4.3). We suggest that supraoptimal crown temperatures occurred for insufficient duration to have detrimentally affected perennial ryegrass growth. It is unknown if tall fescue or chicory experienced supraoptimal crown temperatures as these thresholds appear undefined.

Results likely reflect what would normally be experienced at the experimental location (NW Tasmania), as both T_a and SR were close to long-term averages (1975-2014) (Figure 4.2b, c). Therefore, it is unlikely defoliating to stubble heights of 35 mm or 55 mm in NW Tasmania would compromise growth of any examined species as a consequence of supraoptimal crown temperature stress. When interpreting presented results, the influence of environment as part of the genotype by environment by management interaction should not be ignored. The effect of defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) on crown temperature may negatively affect plant growth and survival in environments characterised by higher summer crown temperatures. Summers in these warmer environments would likely feature higher T_a and daily total SR levels than those experienced at the experimental site. The highest 90th and 75th percentiles of crown temperature were recorded during summer regrowth cycles (Tables 4.2-4.5), when maximum and minimum daily T_a peaked (Figure 4.2a).

In warmer environments, detrimental effects of defoliating to shorter stubble heights may extend beyond elevating apical meristem temperature (located at the crown of vegetative plants) (Rumball 1986; Korte *et al.* 1987; Yang *et al.* 1998). Defoliating to shorter stubble heights may also reduce availability of non-structural carbohydrate (NSC) plant reserves that support respiration during periods of supraoptimal temperature stress, and further accelerate their rate of depletion. During such periods, plants often utilise their NSC reserves

to support respiration (Sullivan and Sprague 1949; Alberda 1965), as supraoptimal temperatures increase rate of respiration but not photosynthesis (White 1973). As the stubble is the primary NSC storage organ in grasses (Fulkerson and Slack 1994; Donaghy *et al.* 2008), defoliating to stubble heights <40 mm reduces the NSC content of plants (Lee *et al.* 2008). By elevating crown temperature, defoliating to shorter stubble heights may further increase respiration rates (Murata and Iyama 1963), potentially exhausting available NSC reserves and culminating in plant death (Sullivan and Sprague 1949).

Further research is required to confirm if defoliating to shorter stubble heights in these warmer environments results in crown temperatures that detrimentally affect plant growth and survival. If leaving higher stubble heights benefits summer growth, research is required to determine the effect of incremental increases in stubble height between 55 mm and 115 mm on crown temperatures. This is because leaving a stubble height of 115 mm for a single regrowth cycle may be a viable option for minimising the exposure of swards to short durations of supraoptimal crown temperature stress (e.g. heat waves), but continuing this practice over multiple regrowth cycles can reduce the growth and nutritive value of grazeable herbage [see Chapter 6 and Lee *et al.* (2007)]. An objective of the proposed research should be to identify stubble heights below 115 mm that effectively suppress crown temperature, while minimising abovementioned limitations.

4.7.2 Species effects

When defoliated to the same stubble height, chicory and second year tall fescue swards experienced less extreme crown temperatures than perennial ryegrass swards. Across summer regrowth cycles of growing season two, 75th and 90th percentiles of perennial ryegrass crown temperatures were as much as 5.9˚C and 6.9˚C higher than chicory crown temperatures, respectively (Tables 4.4 and 4.5). The upper distribution of crown temperature seldom differed between perennial ryegrass and tall fescue in growing season one but differed in half the regrowth cycles of growing season two (Tables 4.2-4.5). When differences occurred in growing season two, perennial ryegrass generally experienced higher crown temperatures. In relevant summer regrowth cycles of growing season two, 75th and 90th percentiles of perennial ryegrass crown temperatures were ≥1.7˚C and ≥3.0˚C higher than tall fescue (Tables 4.4 and 4.5).

Chicory and tall fescue's lower crown temperatures may contribute to their superior growth in environments with hotter summers than NW Tasmania (i.e. south-western and northern Victoria) (Greenwood *et al.* 2006; Tharmaraj *et al.* 2008; Raeside *et al.* 2014). Potential advantages of maintaining cooler crown temperatures during hot summers include reducing the exposure of the apical meristem of vegetative plants to supraoptimal temperature stress (Rumball 1986; Korte *et al.* 1987; Yang *et al.* 1998). Maintaining cooler crown temperatures may also be advantageous in limiting consumption of plant NSC reserves (Sullivan and Sprague 1949; Murata and Iyama 1963). As discussed above, this would reduce the likelihood of plants exhausting NSC reserves, which results in plant death (Sullivan and Sprague 1949).

Chicory and tall fescue are known to be more tolerant of supraoptimal temperature stress than perennial ryegrass [see Chapter 3 and Jiang and Huang (2001b)]. Jiang and Huang (2001b) attributed the superior supraoptimal temperature tolerance of tall fescue *in situ* to the species greater transpirational cooling capacity than seen in perennial ryegrass. This is explained by the species deeper and more extensive root system, which enables tall fescue plants to access soil water stores at greater depth than perennial ryegrass. Whilst transpirational cooling is an important mechanism in maintaining lower plant temperatures (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004), it is unlikely transpiration differences fully explain the cooler crown temperatures of both tall fescue and chicory relative to perennial ryegrass. This is because similar soil water extraction patterns were observed for each species; see soil water content data presented in Chapter 6, section 6.6.1. It is likely the canopy base of the chicory and tall fescue swards were more shaded from incoming SR limiting elevation of crown temperatures (Harrison *et al.* 2015). This cannot be confirmed as LAI was only measured on a relative basis (i.e. only intraspecies comparisons can be made).

4.8 CONCLUSION

Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the likelihood of perennial ryegrass, tall fescue, and chicory experiencing higher crown temperatures in subsequent regrowth cycles. Increases in crown temperature occurred at the upper end of the crown temperature distribution (75th and/or 90th percentiles). Defoliating to shorter

stubble heights in NW Tasmania is unlikely to compromise growth as a result of supraoptimal crown temperatures. The cool-temperate climate of the experimental site would have limited the extent and duration of supraoptimal crown temperatures. Defoliating to shorter stubble heights may negatively affect plant growth and survival in environments featuring higher summer crown temperatures than the experimental site. Research is required to confirm this hypothesis. Chicory and second year tall fescue swards experienced less extreme crown temperatures than perennial ryegrass. This may partly contribute to the cited superior growth of these species in hotter summer environments than NW Tasmania.

Chapter 5: **Imposing summer heat wave conditions in pasture using small-plot outdoor warming systems: A review and recommendations**

5.1 OVERVIEW OF CHAPTER 5

The glasshouse experiment (Chapter 3) showed irrigation mitigated the detrimental effects of supraoptimal temperature stress on perennial ryegrass (*Lolium perenne* L.) growth and survival. Depending on irrigation delivery systems, daily irrigation can be impractical, as practiced in the glasshouse study. Research reported in this chapter tested the hypothesis irrigating more frequently reduces detrimental effects of heat waves on perennial ryegrass growth and short-term persistence. Irrigation was applied every 2, 5, or 10 days to correct soil water deficits. To give on-farm applicability of research findings, this experiment was conducted under field conditions, necessitating the development of an outdoor warming system to reliably simulate heat wave conditions. This chapter also documents the development, and suitability of this artificial warming system for use in forage research.

5.2 ABSTRACT

This paper reviews the suitability of outdoor warming systems for research evaluating options for mitigating detrimental heat wave effects on pastures, with specific reference to south-eastern Australia. Reviewed systems included, retractable infrared reflective covers, field chambers, heating cables, and infrared heater arrays. Freestanding infrared heater arrays were concluded to be the most suitable as they consistently achieve warming, whilst incurring few artefacts (e.g. having minimal effect on light intensity and spectrum, precipitation, and air movement). A modified infrared heater array, with a novel control system designed for evaluating heat wave mitigation options is described. This control system enables the extent of warming to be regulated, whilst applying an equal infrared flux (heating) to all heated plots. This control system was successfully used to test the hypothesis irrigating more frequently reduces detrimental effects of heat waves on perennial ryegrass (*Lolium perenne* L.) growth and short-term persistence (measured via basal frequency). Irrigating more frequently limited the elevation of perennial ryegrass crown temperature under heaters. Median crown temperature elevations under heaters equalled 5.5˚C, 6.5˚C, and 7.0˚C when irrigation was applied every 2, 5, and 10 days, respectively. Due to the mild ambient conditions experienced (mean ambient temperature, 17.2˚C), imposed warming only transiently reduced growth, and failed to affect basal frequency. This study highlights the potential role of this novel control system in future studies, evaluating the effectiveness of strategies for mitigating detrimental heat wave effects on pastures.

5.3 KEYWORDS

Climate change, heatwaves, heat tolerance, thermotolerance

5.4 INTRODUCTION

Globally, summer heat waves are becoming increasingly prevalent (Perkins *et al.* 2012; IPCC 2013; Perkins and Alexander 2013), with many record breaking heat wave events having occurred since the year 2000 (Coumou and Robinson 2013; Steffen *et al.* 2014). Heat waves are problematic for grazing ruminant production in regions dependent on temperate (cool-season) pasture species, such as south-eastern (SE) Australia (Reed 1996; Bell *et al.* 2014). This is due to the minimal heat tolerance (thermotolerance) of many temperate pasture species, including perennial ryegrass (*Lolium perenne* L.) (Mitchell 1956; Beard 1973). High ambient temperatures (≥30˚C) often experienced during SE Australian heat waves challenge the growth and survival of perennial ryegrass, even when irrigated (Table 5.1) (Arcioni *et al.* 1985; Neal *et al.* 2009). Therefore, heat waves are likely to affect the profitability of intensive grazing systems in SE Australia.

Research investigating options for mitigating detrimental heat wave effects on temperate pastures (e.g. alternative species and management) is required. Selecting appropriate research methods necessitates that the applicability of results to the field be considered. Pot studies in controlled-environment facilities are often favoured over field research, due to permitting greater control over abiotic and biotic factors (Dalling *et al.* 2013). Consequently, pot studies, are generally more reproducible and repeatable, and results are simpler to interpret (Passioura 2006; Hohmann *et al.* 2016). Despite these benefits, extrapolating results to field situations can be problematic, due to differences in abiotic and biotic conditions experienced by plants (Ogunkunle and Beckett 1988; Passioura 2006; Wu *et al.* 2011; Poorter *et al.* 2016). Therefore, the value of potential mitigation strategies requires confirmation under field conditions, before being promoted for on-farm adoption.

Field research can be undertaken opportunistically, e.g. testing potential mitigation strategies during naturally occurring heat waves (Smith 2011). However, opportunistic research is logistically difficult, and has many limitations, including: (i) evaluations cannot be undertaken under anticipated future heat wave conditions; and (ii) treatments cannot be compared under heat wave and mean (control) summer conditions. These constraints can be overcome by use of infrastructure that artificially imposes heat waves. Over the last three decades, considerable research has been invested into the design and refinement of small-plot outdoor warming systems (≤20 m^2 plot area) (Aronson and McNulty 2009). This is due to the growing desire of the scientific and general community to understand the

implications of anthropogenic climate change for both natural ecosystems and agroecosystems (Smithers and Smit 1997; Parmesan 2006; Ingram *et al.* 2008; De Jalon *et al.* 2013).

This paper reviews the suitability of these outdoor warming systems for small-plot heat wave research in SE Australian pastures. A detailed description of a modified infrared (IR) heater array, with a novel control system designed for evaluating heat wave mitigation options follows. This paper concludes with a case study, using the modified IR heater array and novel control system to test the hypothesis irrigating more frequently reduces detrimental effects of heat waves on perennial ryegrass growth and short-term persistence.

5.5 SELECTING AN OUTDOOR WARMING SYSTEM

This review describes common outdoor warming systems and appraises their suitability for small-plot heat wave research in pasture. Systems are appraised on their: (i) capacity to provide significant levels of warming (Table 5.1); and (ii) artefacts, e.g. the validity of extrapolating findings to real-world grazing systems. Systems are classified as either passive or active based on their warming method. Passive warming systems operate by retaining the IR radiation emitted from objects warmed by solar radiation (SR) (De Boeck and Nijs 2011), and include retractable IR reflective covers and field chambers. Active warming systems conversely apply additional anthropogenic heat to the field plot, e.g. heating cables/tubes and IR heaters (De Boeck and Nijs 2011).

Table 5.1 Average (Av.) and 90th percentile (90p) of daily maximum (T_{max}) and minimum (T_{min}) summer air temperatures experienced in south-eastern Australian dairying regions between 1997-2016. Mean differences between these values (90p – Av.) represent the extent of air warming required for an outdoor warming system to impose heat wave temperatures during mean summer conditions. This assumes heat waves are "periods of at least three days and two nights for which daily maximum and minimum temperatures exceed the 90th percentile historically experienced for the particular month and location" (Parker et al. 2014). Raw data obtained from the SILO service (www.longpaddock.qld.go.au/silo).

			December		January		February		
	State	Location	Av.	90p	Av.	90p	Av.	90p	Mean, 90p – Av.
T_{max}	NSW	Bega	25.3	31.1	27.3	33.8	26.6	31.9	5.9
		Nowra	25.9	32.0	27.0	33.2	26.4	31.3	5.7
		Wagga Wagga	30.4	36.1	33.0	39.1	31.8	37.8	5.9
	SA	Mt Compass	23.7	33.0	25.6	35.0	25.3	34.5	9.3
		Mt Gambier	23.9	32.8	26.1	35.9	26.3	35.5	9.3
	TAS	Hamilton	22.3	29.0	24.7	32.0	24.5	31.5	7.0
		Ringarooma	20.8	25.0	22.8	27.5	22.7	27.0	4.4
		Smithton	19.6	23.0	21.6	25.0	22.0	25.0	3.3
	VIC	Ellinbank	23.3	31.0	25.7	34.0	25.9	33.4	7.8
		Kerang	30.3	37.6	32.7	40.0	32.1	38.2	6.9
		Terang	23.0	31.5	25.2	35.0	25.4	34.0	9.0
T_{min}	NSW	Bega	13.5	17.3	14.9	18.5	15.2	18.8	3.7
		Nowra	15.0	18.1	16.5	19.7	16.9	20.0	3.1
		Wagga Wagga	14.4	20.1	17.3	22.4	17.1	21.9	5.2
	SA	Mt Compass	13.0	17.5	14.7	19.5	14.8	19.3	4.6
		Mt Gambier	10.4	14.8	12.1	17.0	12.5	17.0	4.6
	TAS	Hamilton	8.5	12.6	9.9	14.5	9.8	14.0	4.3
		Ringarooma	9.6	13.5	11.4	15.5	11.7	15.8	4.0
		Smithton	10.4	14.5	11.7	16.5	12.3	17.5	4.7
	VIC	Ellinbank	11.3	15.5	13.0	17.2	13.4	17.0	4.0
		Kerang	14.0	19.8	16.2	22.5	16.1	21.9	6.0
		Terang	10.1	14.5	11.9	16.5	12.6	17.0	4.5

5.5.1 Passive warming systems

5.5.1.1 Retractable infrared reflective covers

Retractable IR reflective covers (aluminium strips knitted into high density polyethylene mesh) are deployed over plots at night to minimise heat losses, owing to the re-radiation of diurnally accumulated SR as IR radiation (Beier *et al.* 2004). Warming achieved is insufficient for heat wave research, with maximum air and soil warming (50 mm depth) only ~3˚C under optimal operating conditions (clear sky, low wind speed, high SR during the preceding day) (Bruhn *et al.* 2013). Covers may even fail to elicit warming during cloudy conditions, due to the analogous function of clouds and covers (Beier *et al.* 2004). Warming achieved by covers is primarily limited to night-time, and has the undesirable consequence of contracting the diurnal air temperature (T_a) range plants experience; elevation of T_a under

covers is at maximum between mid and late evening and minimum during late afternoon (Beier *et al.* 2004).

5.5.1.2 Field chambers

Field-style greenhouses, tents, and open-top chambers (OTC) are collectively termed field chambers (Aronson and McNulty 2009). Field chambers operate by retaining the IR radiation emitted from objects warmed by SR (Nijskens *et al.* 1985; Wang and Deltour 1999). In many parts of SE Australia field chambers have the potential to elevate maximum daily T_a to heat wave levels during summer (Table 5.1). Mean maximum daily T_a can be elevated in excess of 5˚C (Musil *et al.* 2005; Singh *et al.* 2015), with increases of 12.1˚C reported (Chapin and Shaver 1985). Field chamber warming has the disadvantage of being subject to considerable inter- and intra-day variation, due to being dependent on SR level (i.e. greatest warming occurs on sunny days) (Kennedy 1995b; Bokhorst *et al.* 2013). Such variability, makes it difficult to impose diurnal heat wave T_a for predefined periods, and exposes plants to greater than natural temperature variation. Field chamber warming has the added disadvantage of being diurnally limited (Chapin and Shaver 1985; Rinnan *et al.* 2009; Singh *et al.* 2015). Daily T_a ranges are subsequently amplified as chamber warming is primarily mediated by increases in maximum T_a, due to minimum daily T_a typically occurring just after sunrise when SR is low (Kennedy 1995b). To overcome these limitations, some researchers have complemented field chambers with active surface (IR heaters) or air (duct/fan) warming methods (Norby *et al.* 1997; Pelini *et al.* 2011; Edreira and Otegui 2012; Hoover *et al.* 2014).

Even with active warming, the suitability of field chambers for heat wave research remains questionable, as they incur many artefacts including the reduction/absence of wind (Kennedy 1995b; Wahren *et al.* 2005). Wind artefacts can be reduced by incorporating polyester sides in chambers (Debevec and Maclean 1993), providing the added advantage of facilitating/enhancing gas exchange between external and internal chamber environments (Debevec and Maclean 1993). Similar gas mixing can be achieved by incorporating vents (Kennedy 1995a; Cottee *et al.* 2010; Singh *et al.* 2015), and by elevating chamber walls above the soil surface (Chapin *et al.* 1995). Increasing gas exchange has the disadvantage of reducing chamber warming capacity and subsequent suitability of field chambers for heat wave research (Debevec and Maclean 1993).

Other unwanted artefacts often include a reduced intensity and altered spectral distribution of light underneath chamber coverings (Fangmeier *et al.* 1986; Adaros *et al.* 1989; Kimball *et al.* 1997). Light intensity reductions limit photosynthesis (Debevec and Maclean 1993), with spectral changes altering the physiology and morphology of plants (Kennedy 1995a). Restricting sampling to a central plot in OTC can limit the exposure of sampled plants to light artefacts and ensures they receive precipitation approximating control conditions (Klein *et al.* 2007; Godfree *et al.* 2011). Increasing the opening size of OTC can further minimise precipitation artefacts, but such increases are undesirable, as they occur at the expense of chamber warming capacity (Marion *et al.* 1997). Conversely, field-style greenhouses and tents exclude precipitation altogether.

5.5.2 Active warming

5.5.2.1 Heating cable

Since the 1950's, buried heating cables (heat-resistance electric cables) have been used in soil warming experiments to elevate root-zone temperature by 8-10˚C (Redmond 1955; Cleve *et al.* 1990; De Frenne 2015). Control systems are employed to maintain constant soil temperature differentials (ΔT_s) between heated and unheated plots (Peterjohn *et al.* 1993; Rich *et al.* 2015). Unlike previously discussed passive warming systems, heating cables do not alter light intensity or spectral distribution, precipitation and wind speed (Siebold and von Tiedemann 2012). Other advantages include their ability to warm a significant proportion of the soil profile (Rustad and Fernandez 1998), while maintaining comparable vertical T_s gradients to unheated plots (Siebold and von Tiedemann 2012).

Soil warming with buried heating cable has been criticised for decoupling T_a and T_s (Harte *et al.* 1995; De Boeck and Nijs 2011). Concurrent soil and vegetation warming has been achieved by positioning heating cables above-ground (Ineson *et al.* 1998; Kamp *et al.* 1998; Fitter *et al.* 1999; Xiao *et al.* 2010). Comparable above-ground systems exist, which circulate heated ethylene glycol or hot water through tubes (Hillier *et al.* 1994; Taeger *et al.* 2015). The suitability of above-ground systems for heat wave research is uncertain, as they have only been used to achieve low levels of warming (e.g. 2.5-3.0˚C at the soil surface) (Hillier *et al.* 1994; Ineson *et al.* 1998). Above-ground systems have the disadvantage of being restricted for use in short turf-type vegetation (canopy height <0.2 m), as the insulation

provided by taller plants risks overwarming at the soil surface (Hillier *et al.* 1994). Despite canopy height generally being <0.2 m in studies replicating grazed pastures, this threshold can often be exceeded. Complementing buried heating cables with aboveground warming methods (e.g. IR heaters), may be a preferable method of achieving concurrent soil and vegetation warming (Rich *et al.* 2015).

Deploying buried cables in established swards is not without problems, including the disturbance of soil structure and root systems (Peterjohn *et al.* 1993). A 6 to 12 month lag-time between cable installation and experiment commencement is required for recovery of these parameters (McHale and Mitchell 1996; Rustad and Fernandez 1998; Aronson and McNulty 2009). Many studies include similarly disturbed, but unheated reference plots, to ensure that warming effects are not confused with residual effects from cable burial (Peterjohn *et al.* 1993). Buried heating cables have the additional disadvantage of coming into direct contact with roots, which can adversely affect plant structure and function (Aronson and McNulty 2009). This disadvantage is not unique to buried cables, as above-ground cables/tubes are in contact with the shoot system.

5.5.2.2 Infrared heaters

Infrared heaters emit IR radiation, which directly warms the underlying vegetation and soil. Infrared heating is energetically efficient, eliminating the need to overcome boundary layer resistance, as would be required if the air was warmed first (Kimball 2005). An additional advantage of freestanding IR heating arrays (arrays not deployed in other structures) is their minimal impact on light intensity and spectral distribution, precipitation, and wind speed (Mohammed and Tarpley 2009).

Heat wave conditions have been imposed by modifying the widely used, freestanding IR heating array of Kimball *et al.* (2008). The original array consisted of six 1000 W heaters, deployed at the points of a 3 m diameter regular hexagon. Heaters were placed 1.2 m above the canopy, faced inwards, and angled 45˚ from the horizontal. Uniform warming was achieved within the circular plot area of this array (7.1 m^2), with the intra-plot range in down-going thermal radiation emitted from heaters (operated at maximum capacity) only 150-200 W/m^2 (Kimball *et al.* 2008). Heat wave conditions have been imposed by quadrupling the heating capacity of this array (849 vs. 3395 W/m^2) (Siebers *et al.* 2015;

Siebers *et al.* 2017). This modification enabled the canopy temperatures (T_c) of vegetative soybean (*Glycine max* L.) and maize (*Zea mays* L.) crops to be elevated by an average of 6-9˚C for extended periods (72 h) (Siebers *et al.* 2015; Siebers *et al.* 2017).

Many early studies operated IR heaters at a constant power level (see Table 5.2, "Constant energy flux"). Warming levels were highly variable, due to being dependent on environmental conditions (predominantly wind speed) and stomatal conductance (Hovenden *et al.* 2006; De Boeck and Nijs 2011). High wind speeds reduce down-coming IR radiation via convection heat losses (Kimball 2005). Warming is also reduced by increases in stomatal conductance, and the subsequent capacity of plants to dissipate heat via transpiration (De Boeck *et al.* 2017). Contractions in daily T_c range also occur, due to the increased elevation of minimum relative to maximum T_c, as minimum T_c typically occur at night (Davidson 1969), when wind speeds are low and stomata closed (Van Peer *et al.* 2004; Hovenden *et al.* 2006; Kimball *et al.* 2012). Employing a control system is therefore imperative in minimising/eliminating these artefacts (De Boeck and Nijs 2011).

Control systems have traditionally maintained constant T_c differentials (ΔT_c) between heated and unheated reference plots (see Table 5.2, "Constant temperature elevation"). A key limitation of this system is heated plant responses influence the level of IR radiation applied (De Boeck and Nijs 2011; De Boeck *et al.* 2017). For example, when maintaining a set ΔT_c, IR radiation emitted by heaters would be:

(i) Increased, if the canopy/leaf architecture of heated plants changed to reduce the interception of IR radiation (e.g. leaf curling), or if their transpirational capacity increased relative to unheated plants.
(ii) Decreased, if the transpirational capacity of heated relative to unheated plants declined.

Heated plant responses also influence the level of IR radiation applied by the recently proposed control system of Kimball (2015) (see Table 5.2, "Heated plot canopy conductance"). This control system was developed to eliminate the need for unheated reference plots in recognition of aforementioned examples, when unheated plots are not representative of their heated counterparts (Kimball 2015). More recently, the control system of De Boeck and Nijs (2011) was tested [see Table 5.2, "Unheated reference plot canopy conductance" (De Boeck *et al.* 2017)]. This system combines the benefits of the "constant temperature elevation" and "constant energy flux" methods; i.e. the level of IR radiation applied by heaters is regulated, without the influence of heated plants (see Table

5.2). Responses of plants to additional down-coming IR radiation can be studied using this control system.

Evaluating options for mitigating detrimental heat wave effects on pastures requires an identical IR radiation flux be applied to all heated plots. Achieving this requires selection of one management level or species for regulation purposes. For example, to investigate the effect of irrigation frequency using the 'unheated reference plot canopy conductance' control system, the level of absorbed radiation achieved in all heated plots would equal that required to elevate the T_c of the most frequently irrigated unheated reference plot to the desired level.

If IR heaters are used, it is important experimenters are aware of their limitations. These include shading, reductions in canopy relative humidity (RH), and sensitivity of applied heating to wind speed. Shading, while often minimal [2%, when sun at zenith for the popularised design of Kimball *et al.* (2012)], is an unavoidable effect of IR heating infrastructure. Many studies deploy non-functional infrastructure over unheated reference plots to standardise shading level (Nijs *et al.* 1996; Kimball 2005). Another unintended effect is reduced canopy level RH (De Boeck and Nijs 2011), as IR heating is equivalent to air warming at constant absolute humidity (Kimball 2005). This can be corrected using the addition of supplemental irrigation (Kimball 2005). However, when studying heat waves this correction is not required, as RH is often depressed during heat waves (De Boeck *et al.* 2010).

Table 5.2 Summary of the main infrared (IR) heater control systems, and their relative advantages and disadvantages.

IR heater operating system	Brief description	Advantages	Disadvantages	Examples
Constant energy flux	Heaters operated at a constant power level (e.g. no control system)	• Level of IR radiation applied independent of heated plant responses • Simple to operate	• Extent of warming unregulated • Highly variable level of warming achieved • Contract daily temperature range	Harte and Shaw (1995) Wan *et al.* (2002) Noormets *et al.* (2004) Hovenden *et al.* (2006)
Constant temperature elevation	Heaters regulated to maintain a constant canopy/leaf temperature differential between heated and unheated reference plots	• Regulated level of applied IR radiation • Moderately simple to operate	• Level of applied IR radiation dependent on heated plant responses	Nijs *et al.* (1996) Kimball (2005)
Heated plot canopy conductance	a. Canopy conductance of heated plot calculated b. Previous step used in calculating the additional down-coming IR radiation (R_h) required to increase heated plot canopy temperature by the target level c. Heater output increased until required R_h achieved	• Regulated level of applied IR radiation	• Level of applied IR radiation dependent on heated plant responses • Considerable capital cost (required sensors) • High level of complexity	Kimball (2015)
Unheated reference plot canopy conductance	a. Canopy conductance of unheated reference plot calculated b. Previous step used in calculating the theoretical canopy temperature of the unheated reference plot, if air temperature was elevated by the target level c. Amount of absorbed radiation (R_{abs}) required to achieve the theoretical canopy temperature calculated d. Heaters output increased until required R_{abs} achieved	• Regulated level of applied IR radiation • Level of applied IR radiation independent of heated plant responses • Based on air temperature differences, thus easily used to replicate heat wave forecasts	• Considerable capital cost (required sensors) • High level of complexity	De Boeck *et al.* (2017)

5.5.3 Review conclusion

Freestanding IR heater arrays appear the most viable option for small-plot heat wave research in pastures. Justification is provided by their capacity to predictably impose heat wave conditions, while introducing few unwanted artefacts if an appropriate control system is employed. Infrared heaters can be used in concert with heating cables/tubes, if deeper soil warming is required. The following section details an economical freestanding IR heater array and control system, tested in an accompanying case study. The control system operates by maintaining a constant day/night ΔT_c differential between one pair of heated and unheated reference plots, with the IR radiation required to achieve this level of warming applied to all other heated plots. This enables the effectiveness of different management strategies, or species, in mitigating the detrimental effects of heat wave conditions to be compared, and to the authors' knowledge is the first example of such a control system. A constant ΔT_c rather than the 'unheated reference plot canopy conductance' method is applied to minimise the cost and complexity of the control system. The latter system requires considerable expenditure on sensors, limiting its suitability for projects with limited financial resources.

5.6 DESCRIPTION OF A MODIFIED INFRARED HEATER ARRAY AND NOVEL CONTROL SYSTEM

All electrical componentry was constructed in accordance with Australian Standards by a qualified electronics technician, with the system approved by a qualified electrician. A qualified electrician monitored the system during operation. This section provides only a brief description of the modified IR heater array and control system, prepared to the best of the authors' abilities. The authors accept no liability for the accuracy of this description, nor any damages or injury resulting from replication. All mentioned componentry is followed by an item number in parenthesis. Item numbers correspond with those used in Supplementary Table 5.7, which provides a detailed description of listed componentry.

5.6.1 Infrared heaters

Akin to Kimball *et al.* (2008), each heater consisted of a 1000 W heating element (1), housed within an aluminium reflector (2). Heaters were water-proofed using high temperature resistant silicone (3). Each heater was connected to a 2-core plus earth, silicone sheathed, power supply cable (4), which terminated with a 3-pin plug.

5.6.2 Infrared heater array

A modified version of the freestanding IR heating array developed by Kimball *et al.* (2008) was used (discussed earlier). Heat wave conditions were previously imposed by quadrupling the heating capacity of this array from 849 to 3395 W/m^2 (Siebers *et al.* 2015; Siebers *et al.* 2017). This was achieved by increasing the number of heaters from 6 to 24 (Siebers *et al.* 2015; Siebers *et al.* 2017), which incurs greater infrastructure and ongoing power costs (Kimball *et al.* 2012). Alternatively, the required heating capacity (3395 W m^2) can be attained by reducing the heated plot area to a quarter of the original (1.77 vs. 7.1 m^2). This paper describes an array designed according to the latter approach.

The modified array heated a 1.77 m^2 circular plot with six 1000 W heaters, deployed at the points of a 1.5 m diameter regular hexagon (Figures 5.1 and 5.4a). Heaters were positioned so the centre of the heating elements was elevated 0.6 m above the canopy, faced inwards, and angled 45˚ from the horizontal. The height of heaters above the canopy equalled 0.4 x array diameter (1.5 m). This scaling factor was used by Kimball and Conley (2009) to upscale the original array of Kimball *et al.* (2008) to a 5 m diameter. Heaters were positioned to place the centre of heating elements directly above the plot perimeter.

All heaters in an array were supported by a single portable stand consisting of six vertical 1.6 m galvanised steel poles (Figure 5.1 and 5.4a). Poles were located at the points of a 1.816 m diameter regular hexagon; i.e. poles were placed 158 mm outside the heating array perimeter. Neighbouring pairs of poles were joined using two horizontal 0.878 m sections of mild steel round bar, placed at 0.04 and 1.60 m heights. Heaters were connected to each pole via individual clamps (refer to Figures 5.2a, b and 5.4b for clamp details).

Non-functional arrays were placed over unheated reference plots enabling the comparison of heated and unheated plots that had received equal shading. With one exception,

non-functional arrays were identical to their functional counterparts; pseudo-heaters were used, which consisted of 254 mm lengths of polyvinyl chloride pipe (110 mm outer diameter; Figure 5.4b). Pipe with a similar cross-section-area to reflector housings was used being a more economical option than either non-powered heater units or empty reflector housings (cost saving ranged between $AU 329-662/array). Pipe lengths were painted with aluminium pigmented paint to mimic reflectors.

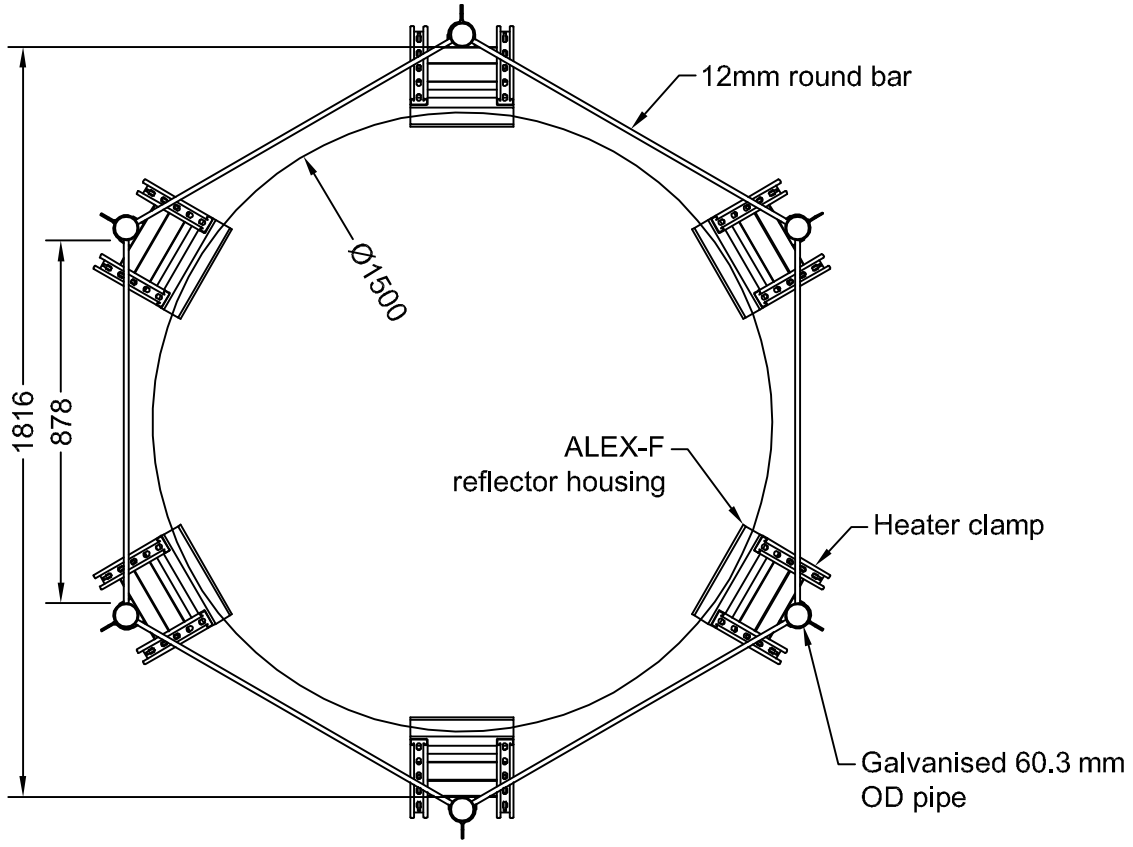

Figure 5.1 Top view of the infrared heater array, with all measurement in mm. A heater clamp connects each heater reflector housing (ALEX-F) to a 60.3 mm outer diameter (OD) galvanised pole. Note, Ø symbolises the heated plot area diameter, which is demarked by the circle within the array.

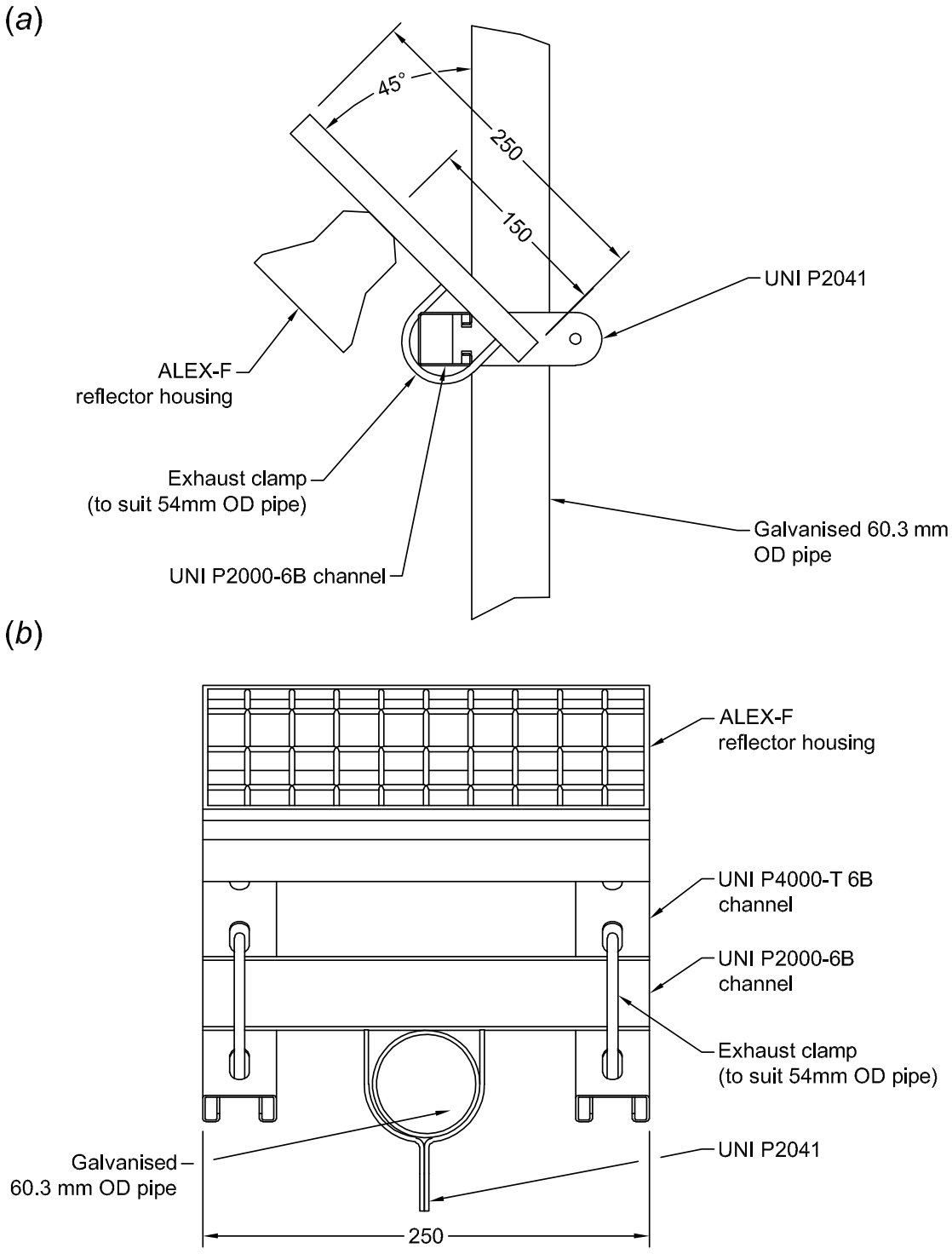

Figure 5.2 Side (*a*) and bottom (*b*) view of the clamp used to support both heaters and pseudo-heaters, with all unspecified measurements in mm. The clamp is depicted supporting a heater reflector housing (ALEX-F), and is connected to a 60.3 mm outer diameter (OD) galvanised pole. Parts commencing with the 'UNI' prefix were manufactured by Unistrut® (Atkore International Group; Harvey, IL, USA).

5.6.3 Control system

5.6.3.1 Operating principles

The control system was designed to apply equal levels of power to all functional IR heater arrays. This control system regulated three functional IR heater arrays and could be adapted to support a higher number. Mains power [240 V alternating current (AC), 50 Hz] supplied to IR heater arrays was regulated to maintain a constant tiller temperature differential (ΔT_t) between one pair of unheated reference and heated plots (8˚C in the accompanying case study). Tiller temperature was monitored in nominated plots via a temperature monitoring/heating controller unit, which computed the power required to maintain the target ΔT_t at 4 s intervals. Each functional IR heater array was serviced by a single mains power supply unit that regulated mains power supply to heaters, based upon requirements computed by the temperature monitoring/heater control unit. Detailed explanation of the system's componentry is provided below. A diagrammatic overview of the system is presented in Figure 5.3a.

An advantage of this control system is an identical IR radiation flux is applied by all IR heater arrays, whilst the level of applied warming is regulated to avoid the disadvantages incurred by constant energy flux operation (Table 5.2). This enables comparison of contrasting management levels or species ability to mitigate detrimental effects of imposed heat wave conditions.

A disadvantage of the control system, is the level of applied IR radiation is affected by the responses of plants in the heated plot used for regulation purposes. When evaluating strategies for mitigating detrimental effects of heat wave conditions, this limitation can be minimised by selecting treatments least likely to be adversely affected by applied heating for regulating the level of applied IR radiation; i.e. if examining:

- Contrasting irrigation frequencies, the most frequent irrigation schedule should be used.
- Different species, the most heat tolerant species should be used.

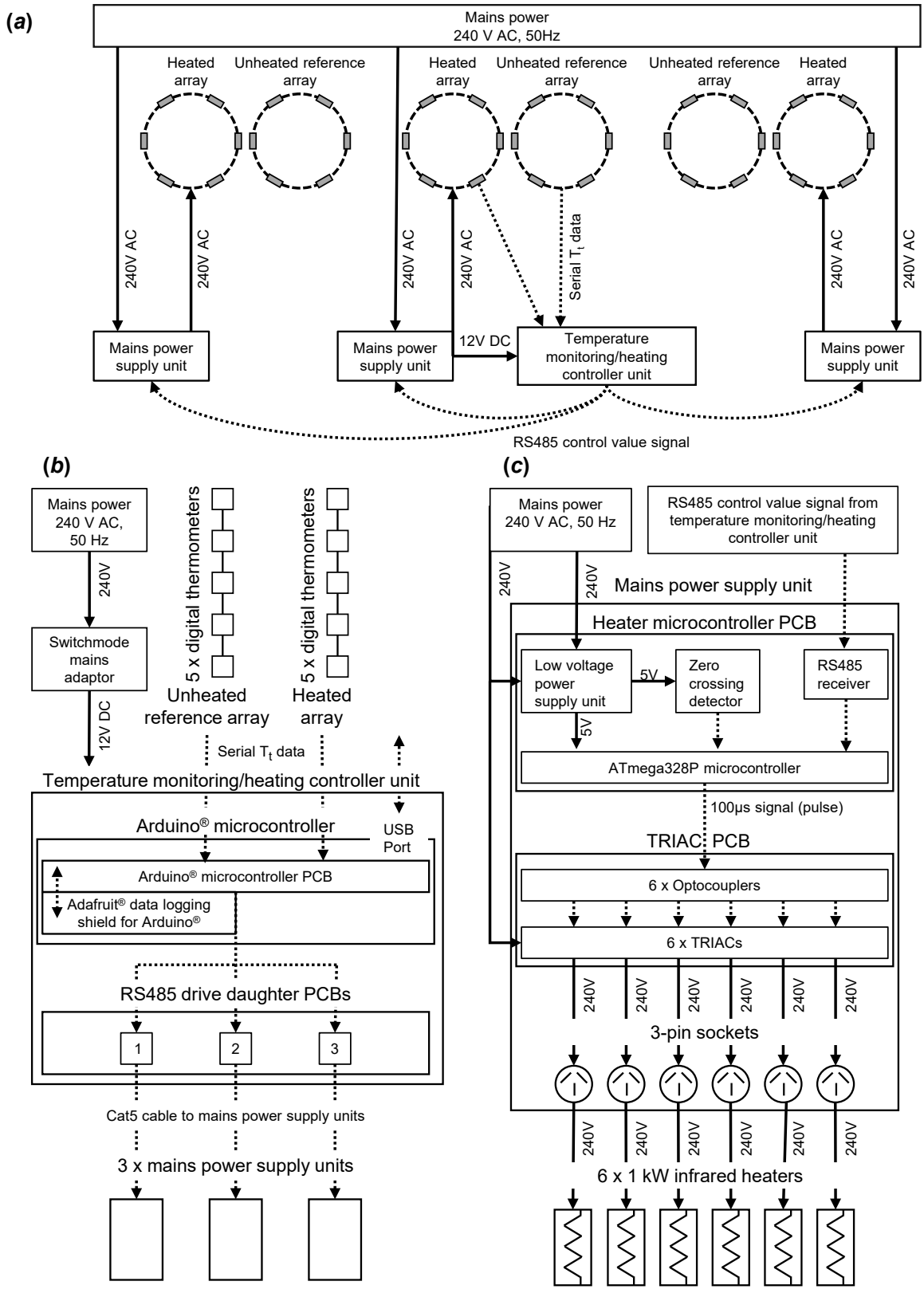

Figure 5.3 Schematics of the (*a*) overall infrared heating control system, (*b*) temperature monitoring/heating controller unit, and a (*c*) mains power supply unit. Abbreviations include: (i) alternating current, AC; (ii) direct current, DC; (iii) printed circuit board, PCB; (iv) tiller temperature, T_t; and (v) triode for alternating current, TRIAC. Power and signal (information) flow is represented by solid (——) and dashed (▪ ▪ ▪ ▪) lines, respectively.

5.6.3.2 Temperature monitoring/heating controller unit

A single temperature monitoring/heating level controller unit serviced the entire system (Figure 5.3a, b and 5.4c). Printed circuit boards (PCBs) comprising this unit included an Arduino® microcontroller (5), and three RS485 driver daughter PCBs. An Adafruit® data logging shield for Arduino® (6) was attached to the Arduino® microcontroller. All listed hardware was housed in a single weather-proof enclosure. Power was supplied to the unit via a 3-pin socket in the closest mains power supply unit (detailed below). Mains power was first converted to a 12V direct current supply via a switchmode mains adaptor (7).

Tiller temperature was monitored in one pair of unheated reference and heated plots using the Arduino® microcontroller. Temperature was measured in each plot using five digital thermometers (8). Thermometers servicing a plot were 'daisy chained' on the same three cores of a Category 5e (Cat5e) cable (9) connected to the Arduino® microcontroller via a 3-pin plug. Thermometers were sequentially teed off the Cat5e cable via small PCBs (one per thermometer) contained in weather-proof enclosures (Figure 5.4d). Between each thermometer and PCB was a 0.845 m length of 3-core ribbon cable (10) followed by a short section of round screened cable (11). Joins between thermometers and ribbon cable were weather-proofed using a non-acidic silicone compound (12).

In each plot, thermometers were positioned in five locations including the plot centre, and 375 mm inwards from the midpoint of sides 1, 3, 4, and 6 of the 1.5 m diameter regular hexagon used to position heaters. Thermometers were attached to tillers at 0.5 x canopy height via a micro-clamp (Figure 5.4e). Each micro-clamp consisted of a 26 mm alligator clip, with one ring terminal (8 mm stud) crimped onto either jaw. Thermometers were pressed against the tiller by the lower jaw. The inside and outside of the lower jaw was insulated with solid pieces (18 mm long, 10 mm wide, and 4 mm thick) of white rubber tape and foam, respectively.

Temperature data from each monitored plot was averaged every 4 s by the Arduino® microcontroller and fed into a proportional control program operating to the following formula:

$$\text{Control value} = \{[(\mu_{\text{uh}} + t) - \mu_{\text{h}}] \times g\} + c$$

where, μ_{uh} is the mean unheated reference plot temperature (˚C), t is the offset temperature (8˚C), μ_{h} is the mean heated plot temperature (˚C), g is the gain value (1˚C), and c is the control offset (6˚C). Predetermined values were obtained from field testing. Arduino® microcontroller firmware was developed using the Arduino® Integrated Development Environment; C++ language was used (script available on request).

Two pins in the Arduino® microcontroller enabled communication with RS485 drive daughter PCBs. Each RS485 drive daughter PCB sent control values serially (9600 baud) to an RS485 receiver in a separate heater microcontroller (mains power supply unit) via a Cat5e cable. Values received by heater microcontrollers were curtailed between 0-10, which equalled the number of consecutive half cycles of AC mains power supplied to heaters in each set of ten. Control values of ten and zero corresponded to full and no power, respectively.

5.6.3.3 Mains power supply unit

Each functional IR heater array was serviced by an individual mains power supply unit contained within a weather-proof enclosure (Figures 5.3a, c and 5.4f). Mains power was delivered to each mains power supply unit via a 90 m extension cable (13) permitting mains power supply units to be moved around the experimental site. As a safety precaution, power servicing each mains power supply unit, passed through a residual current device.

Major subunits of each mains power supply unit included the heater microcontroller (Figure 5.4g), and triode for alternating current (TRIAC) output PCB (Figure 5.4h). Key components of the heater microcontroller PCB included an ATmega328P microcontroller (14), ‘low voltage power supply unit’ (transformer), and ‘zero crossing detector’. Serial values transmitted from the temperature monitoring/heating level controller unit were received by the ATmega328P microcontroller via a separate daughter PCB (RS485 receiver). The ATmega328P microcontroller produced a 100 µs pulse on each half cycle that the heaters

were required to be turned on; 100 μs pulses were sent to the TRIAC output PCB via a 3-pin connector. Generation of such pulses required the ATmega328P microcontroller to count the number half cycles. Number of half cycles were counted using the zero crossing detector, which produced a pulse at every half cycle to interrupt the ATmega328P microcontroller. Power was supplied to both the ATmega328P microcontroller and zero crossing detector via a low voltage power supply unit, which reduced the voltage from 240 to 5 V. ATmega328P microcontroller firmware was developed using the Arduino® Integrated Development Environment; C++ language was used (script available on request).

The TRIAC PCB consisted of six TRIAC circuits; each TRIAC circuit had a separate fuse, and modulated mains power supply to an individual heater. This approach was preferable to those undertaken in previous studies which modulated power supply to all heaters via a single device [e.g. Kimball (2005)]. This is because less stress is placed on each power modulation device reducing the probability of losing power to all heaters. As TRIACs were opto-isolated, all light-emitting diode drivers were connected in series and driven from one transistor. This permitted the single pulse emitted by the ATmega328P to simultaneously trigger each TRIAC to supply mains power to heaters. Heaters were connected to the mains power supply unit via 3-pin plugs and sockets. TRIACs were opto-isolated to protect the heater microcontroller PCB from mains power. Risk of overheating was minimised by all TRIACs being mounted on heat-sink, with a fan used to generate air flow over TRIACs.

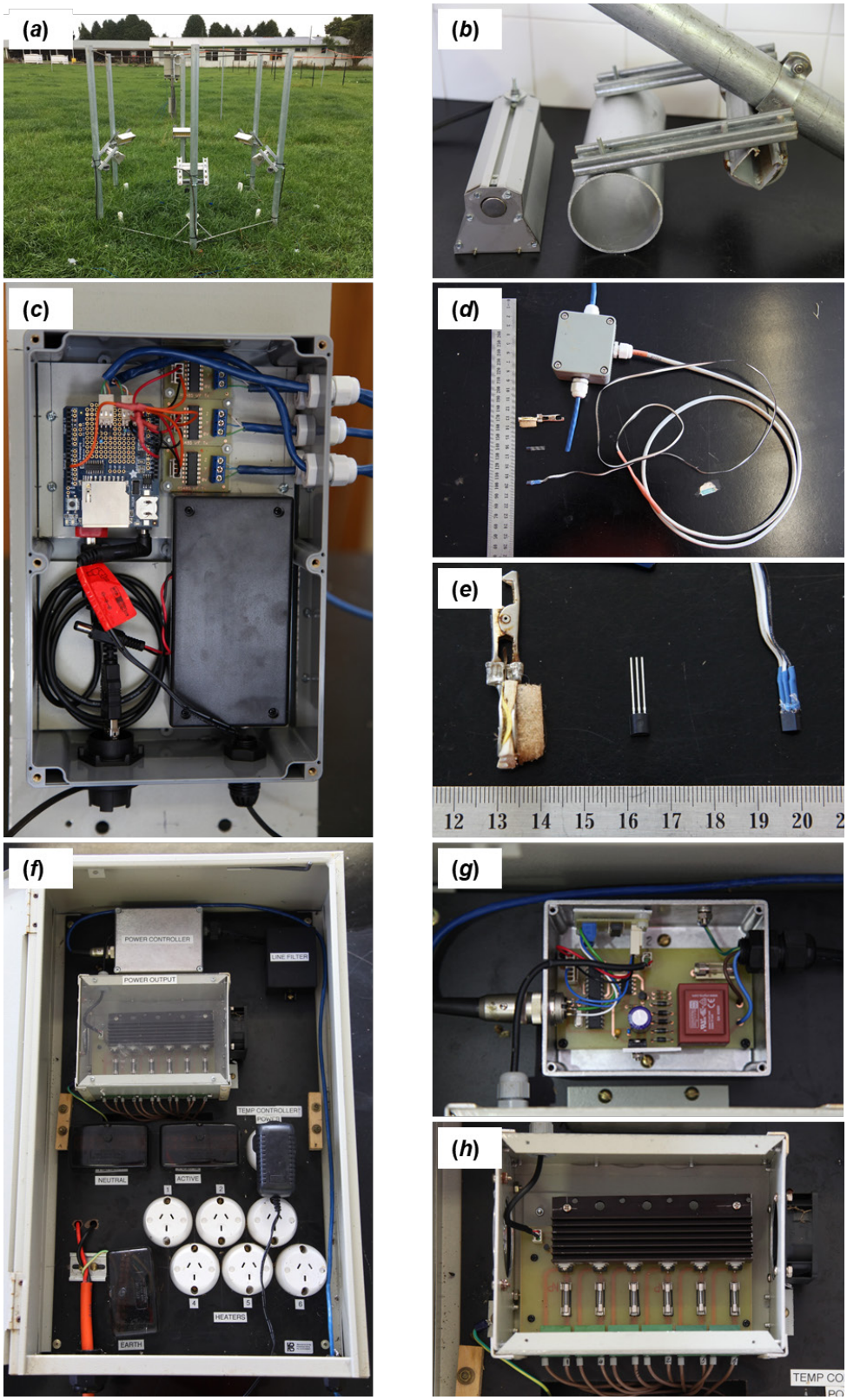

Figure 5.4 Photographs of: (*a*) infrared heater array; (*b*) heater (left) and pseudo-heater (right); (*c*) temperature monitoring/heating controller unit; (*d*) digital thermometer, teed off from the Category 5e cable via a small printed circuit board (PCB) in a weather-proof enclosure; (*e*) side view of micro-clamp used to attach a digital thermometer to a tiller (left), digital thermometer (centre), and digital thermometer attached to 3-core ribbon cable (right); (*f*) mains power supply unit; (*g*) heater microcontroller; and (*h*) triode for alternating current (TRIAC) output PCB.

5.7 CASE STUDY

The modified IR heater array and novel control system previously discussed were employed to test the hypothesis irrigating more frequently reduces detrimental effects of heat waves on perennial ryegrass growth and short-term persistence (measured via basal frequency). This hypothesis was derived from a previous glasshouse study, which showed irrigation (daily to through drainage) mitigated the detrimental effects of prolonged heat wave conditions (day/night Ta of 38/25˚C for 18 days) on perennial ryegrass growth (Chapter 3).

Applying irrigation more frequently to return soil water content to field capacity has many advantages for swards experiencing heat wave conditions. These include maintaining plants at a high transpirational capacity, as transpiration can depress the T_c of forages by >7˚C below T_a (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004; Richardson 2004). Irrigation applied as a spray can also depress plant temperatures by conduction (transfer of heat from plant to water), and evaporation on plant surfaces (Kliewer and Schultz 1973; Aljibury *et al.* 1975). Additionally, maintaining a high soil water content reduces soil susceptibility to temperature increases (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015). As it can be impractical to irrigate daily, this study evaluated the potential of less frequent irrigation schedules to mitigate detrimental heat wave effects on perennial ryegrass.

5.7.1 Materials and methods

5.7.1.1 Site description

This study was conducted at the Tasmanian Institute of Agriculture Dairy Research Facility in north-west Tasmania (41˚08'S, 145˚77'E; elevation 155.0 m). The experimental site supported a newly established (108 days post-sowing), irrigated, perennial ryegrass cv. Bealey® (NEA2, non-toxic endophyte) monoculture. The site had minimal undulations, and was characterised by a Red Mesotrophic Haplic Ferrosol soil (Isbell 1996).

5.7.1.2 Experimental design

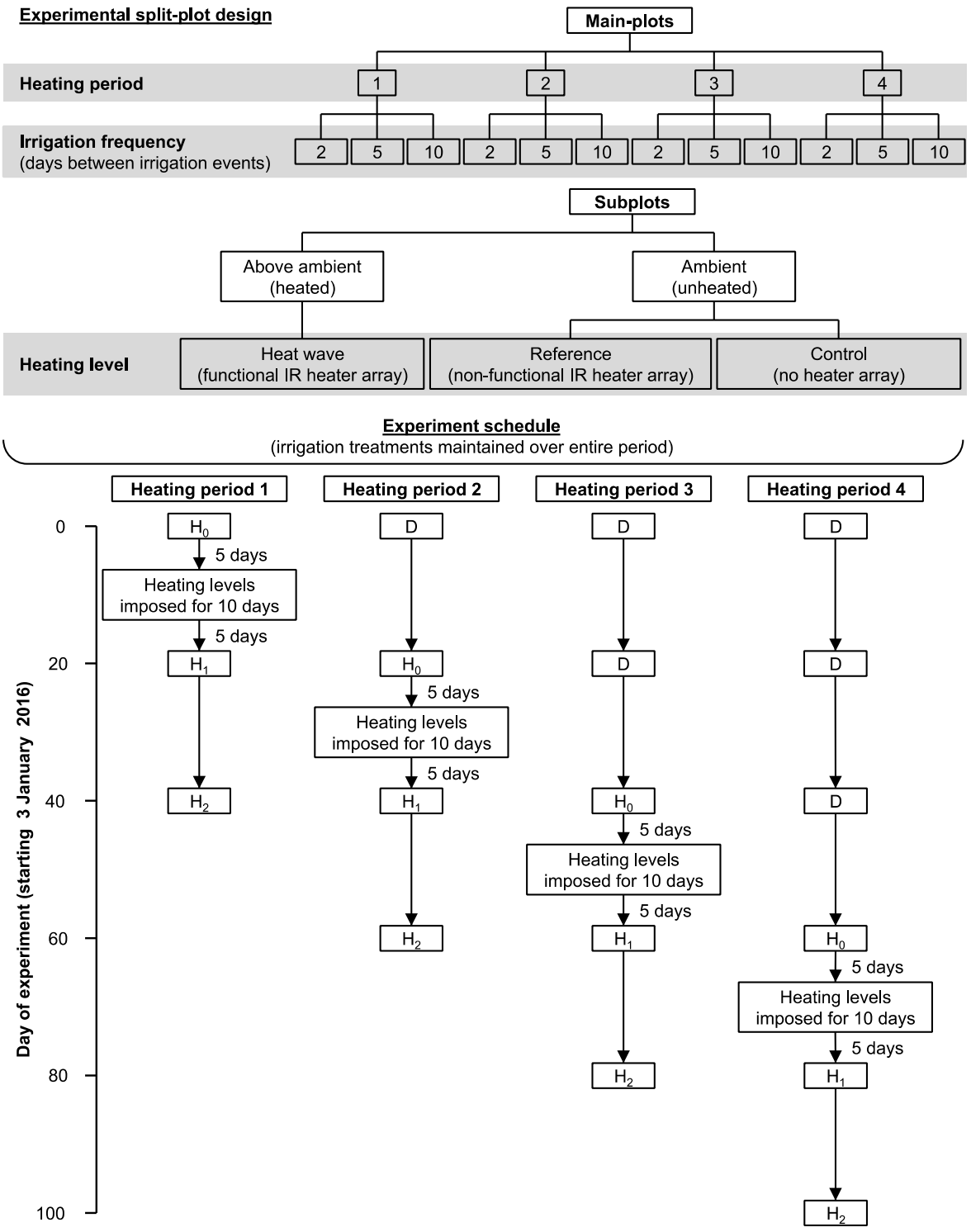

Figure 5.5 Diagrammatic schematic of the experimental split-plot design and schedule. Abbreviations include: (i) defoliated, D; (ii) harvest (H), including a covariate harvest (H_0), and harvests one (H_1) and two (H_2); and (iii) infrared, IR.

Treatments commenced on the 3 January 2016, with the experiment arranged in a split-plot design. Combinations of time of heating level imposition (heating period) and irrigation frequency (days between irrigation events) formed the main-plots, with subplots divided by heating level (Figure 5.5). A completely randomised design was observed when arranging main-plots within the experimental area, and subplots within main-plots. A total of 36 subplots were included (four heating periods by three irrigation frequencies by three heating levels), which were ≥6 m apart.

Subplots were defoliated every 20 days, with heating level treatments imposed on a different set of main-plots during each of the first four regrowth cycles (time between successive defoliation/harvest events). Each set of main-plots included 9 subplots, comprising all combinations of the three irrigation frequencies and three heating levels. Subsequently, each set of main-plots represented a separate heating period and served a as replicate. Each heating period included a harvest: (i) immediately prior to the regrowth cycle, when heating levels were imposed (H_0); (ii) after the regrowth cycle in which heating levels were imposed (H_1); and (iii) after the recovery regrowth cycle (H_2) following H_1. Ambient (unheated) weather conditions during these regrowth cycles (e.g. H_0-H_1 and H_1-H_2) are provided in Table 5.3.

Irrigation frequency treatment levels (2, 5, or 10 days between irrigation events) were imposed at experiment commencement. Precipitation deficits were replenished at each irrigation event and were calculated as the cumulative difference between precipitation and estimated pasture evapotranspiration (ET) under ambient (unheated) conditions (Allen *et al.* 1998). Zero was the maximum obtainable precipitation deficit. Water was delivered to subplots via spray irrigation at 6 mm/h and a distribution uniformity >80%. Total accumulated ET, rainfall, and irrigation is presented for each regrowth cycle in Table 5.3.

Heating levels included heat wave (functional IR heater array), unheated reference (non-functional IR heater array), and control (no-infrastructure) treatments. Heat wave conditions were imposed using the modified freestanding IR heater array and novel control system (Section 5.6). A target 8˚C ΔT_t was maintained between unheated reference and heat wave subplots that were irrigated every 2 days. Heating levels were imposed between days 5 and 15 of regrowth cycle, H_0-H_1.

Table 5.3 Ambient weather conditions and irrigation records for regrowth cycles constituting each heating period; i.e. regrowth cycle when heating levels were imposed (H_0-H_1), and the accompanying recovery regrowth cycle (H_1-H_2). Weather conditions include mean maximum (max.) and minimum (min.) daily air temperature, vapour pressure deficit (VPD), and solar radiation (SR, recorded during the 3 h either side of solar noon). Other parameters include mean daily wind speed, total evapotranspiration, and total rainfall. Irrigation records are presented for each tested irrigation frequency.

Heating period	Regrowth cycle	Temperature (°C)		VPD (kPa)		SR (W m^{-2})		Mean wind speed (m s^{-1})	Total ET (mm)	Total rainfall (mm)	Total irrigation (mm)		
		Max.	Min.	Max.	Min.	Max.	Min.				2 day	5 day	10 day
1	H_0-H_1	22.8	12.7	1.90	0.44	1110	370	5.9	76	3	78	55	38
1 2	H_1-H_2 H_0-H_1	22.4	13.9	1.11	0.16	1121	252	5.3	62	61	53	61	80
2 3	H_1-H_2 H_0-H_1	20.3	12.3	0.87	0.12	962	163	5.1	48	51	49	50	33
3 4	H_1-H_2 H_0-H_1	20.4	13.2	1.12	0.20	846	178	4.6	40	41	42	26	23
4	H_1-H_2	17.5	9.5	0.74	0.24	888	122	4.6	34	8	31	38	38
Overall for 100 day period		20.7	12.3	1.90	0.12	985	217	5.1	260	165	253	230	212

5.7.1.3 Experimental management

Nitrogen (N, as urea; 46% N) was applied after each defoliation/harvest event at 30 kg N/ha. No weed control was applied during the experiment, as the botanical composition of harvested herbage was always >90% perennial ryegrass on a dry matter (DM) basis.

5.7.1.4 Measurements

Subplots were cut with a rotary lawnmower to a 55 mm stubble height at each defoliation/harvest event. Cut herbage was removed from plots. Harvested (H_0, H_1, and H_2) herbage was weighed, with a subsample (~200 g fresh weight) dried to constant weight in a forced-draught oven; 60˚C for 48 h. Daily DM growth rates (kg DM/ha.day) were then calculated.

Basal frequency was measured shortly after each harvest, by placing a 1 m^2 quadrat over the centre of subplots. Quadrats were divided into 0.01 m^2 squares (i.e. 100 squares/quadrat), with the number of squares where perennial ryegrass tillers were present (i.e. shoot-root system interface) recorded.

Crown temperature sampling occurred at 20 min intervals in each subplot during regrowth cycle, H_0-H_1. Measurements were restricted to the 10 days, when heating levels were imposed. Crown temperatures were measured using four self-contained, waterproof thermometers per subplot (DS1921G Thermochron® iButton® Dallas Semiconductors; Maxim integrated™; San Jose, CA, USA), which are accurate to ±1˚C between -40˚C to +85˚C. Thermometers were vertically inserted into the crown of plants, as detailed by Harrison *et al.* (2015). Thermometers were located 375 mm inwards from the midpoint of sides 1, 3, 4, and 6 of the regular hexagon used to position heaters.

5.7.1.5 Statistical analyses

Data from all examined variables were analysed according to a split-plot design, with treatment factors assigned as stated in the *Experimental design* section. All differences discussed were significant at the $P<0.05$ level.

Daily growth rate and basal frequency data were analysed as repeated measures, with H_1 and H_2 measurements included and H_0 incorporated as a covariate. Quantile-quantile plots of residuals were examined, with no transformation required. Data was analysed using the PROC MIXED procedure in SAS 9.3 (SAS for Windows Release 9.3; SAS Institute, Cary, NC, USA). The first analysis (infrastructure analysis) undertaken, compared control and unheated reference heating levels. If no significant difference was detected, both control and unheated reference heating levels were combined to create the new variable, ambient heating level. When appropriate, this new variable was used in an accompanying analysis that included the following fixed effects: (i) heating level (heat wave vs. control vs. unheated reference heating levels, or heat wave vs. ambient heating levels); (ii) irrigation frequency (2 vs. 5 vs. 10 day); and (iii) the interaction between heating level by irrigation frequency. If fixed effects were significant, the specific analysis was re-run with measurement time (H_1 and H_2) included as a fixed effect. *P*-values arising from multiple comparisons were adjusted for multiplicity using the Tukey-Kramer method.

Crown temperature data was analysed using quantile regression via the QUANTREG procedure in SAS 9.3 (Koenker 2005). Analysed crown temperature data was restricted to the middle 8 days of the 10 day period when heating level treatments were imposed. Crown temperature data was analysed as the difference between: (i) absolute values; and the (ii) extent of crown temperature elevation (differential between paired heat wave and unheated reference subplots) under contrasting irrigation frequency treatment levels. Prior to quantile regression, an autoregressive time series model of order two was fitted to the mean variable. Also included was: (i) a linear predictor, being hours since start (HSS) of measurement period, which removed linear changes; (ii) a quadratic trend HSS^{-2}, which removed curvature; and (iii) cosine and sine terms based on the HSS variable, which removed diurnal variation. Cosine and sine terms were defined as:

$$\text{HSS\_2}c = \cos\left(2 \times 3.14159 \times \frac{\text{HSS}}{24}\right),$$

$$\text{HSS\_2s} = \sin\left(2 \times 3.14159 \times \frac{\text{HSS}}{24}\right),$$

$$\text{HSS\_4}c = \cos\left(2 \times 3.14159 \times \frac{\text{HSS}}{24}\right),$$

$$\text{HSS\_4s} = \sin\left(4 \times 3.14159 \times \frac{\text{HSS}}{24}\right).$$

The autoregressive model was developed with PROC AUTOREG in SAS 9.3. Residuals obtained from the model were used in the quantile regression to assess treatment effects. Quantile regression was used to model the proportion of the time-series adjusted crown temperature data that fell below the 10th, 25th, 50th, 75th, and 90th percentiles. The analysis structure followed for each percentile was identical to that previously described for daily growth rate and basal frequency data. Associated *P*-values of pairwise comparisons were multiplicity-adjusted using simulation (Westfall *et al.* 2011).

In all analyses, non-significant fixed effect interactions were removed for simplification purposes.

5.7.2 Results and discussion

5.7.2.1 Perennial ryegrass monoculture responses

An interaction between heating level and measurement time was observed on daily growth rates ($P<0.01$, Table 5.4). During regrowth cycles when heating levels were imposed (H_0-H_1), daily growth rates achieved in heat wave subplots were 23% less than their ambient (unheated) counterparts (43.1 vs 56.1 kg DM/ha.day). Detrimental heat wave effects were transient, with daily growth rates in the recovery regrowth cycle (H_1-H_2) unaffected by prior heat wave exposure. The limited detrimental effect of heat wave conditions on perennial ryegrass growth is explained by the short duration of damaging high crown temperatures (>32˚C) (Peacock 1975b). During the 8 analysed days of the 10 day heat wave period, crown temperatures were only: (i) ≥29˚C, 25% of the time; and (ii) ≥31˚C, 10% of the time (Figure 5.6a). This may explain why no considerable changes in perennial ryegrass basal frequency were induced by imposed heat wave conditions ($P>0.05$, Table 5.4).

Table 5.4 Growth rates (GR, kg of dry matter/ha.day) and basal frequency (maximum value of 100) of perennial ryegrass swards exposed to contrasting irrigation frequency (I) and heating level (HL) treatments. Irrigation was applied every 2, 5, or 10 days. Heating levels included control (no-infrastructure), reference (non-functional infrared heater array), ambient (control and reference combined), and heat wave (functional infrared heater array). Interaction of fixed terms (FT) is omitted, due to being non-significant ($P \geq 0.05$). Regrowth cycles are only presented for significant ($P < 0.05$) fixed terms; i.e. regrowth cycle when heating level treatments were imposed (H_0-H_1), and recovery regrowth cycle (H_1-H_2). Values are least-square means ± one pooled standard error.

Parameter	Analysis	FT	*P*-value	Treatment level	Overall	H_0-H_1	H_1-H_2
GR	Infrastructure	HL	≥0.05	Control	53.7 ± 2.3	-	-
				Reference	58.3 ± 4.6	-	-
	Ambient vs. heat wave	I	≥0.05	2 day	52.9 ± 3.0	-	-
				5 day	52.2 ± 2.9	-	-
				10 day	49.1 ± 2.9	-	-
		HL	<0.05	Ambient	55.8 ± 2.0**A**	56.1 ± 2.1**Aa**	55.6 ± 2.1**Aa**
				Heat wave	46.9 ± 2.0**B**	43.1 ± 3.1**Bb**	50.7 ± 3.1**Aa**
Basal frequency	Infrastructure	HL	≥0.05	Control	88.3 ± 0.9	-	-
				Reference	89.3 ± 0.9	-	-
	Ambient vs. heat wave	I	≥0.05	2 day	88.3 ± 1.0	-	-
				5 day	88.0 ± 1.1	-	-
				10 day	88.2 ± 1.1	-	-
		HL	≥0.05	Ambient	88.5 ± 0.7	-	-
				Heat wave	87.8 ± 1.0	-	-

Values followed by the same letter do not differ ($P \geq 0.05$); uppercase letters compare between treatment levels, while lowercase letters compare between regrowth periods within a treatment level.

Irrigating more frequently did not reduce detrimental heat wave effects on daily growth rates (irrigation frequency by heating level interaction, $P > 0.05$), but did limit crown temperature elevation under heaters (differential between paired heat wave and unheated reference subplots). Irrigation frequency affected the extent of crown temperature elevation under heaters at the: (i) 50th percentile ($P < 0.0001$); (ii) 75th percentile ($P < 0.01$); and (iii) 90th percentile ($P < 0.0001$) (Figure 5.6b and Table 5.5). Crown temperature elevations achieved on these occasions were lower when irrigation was applied every 2 days, relative to 5 or 10 days. Only at the 10th ($P = 0.71$) and 25th ($P = 0.73$) percentiles did irrigation frequency fail to affect the extent of crown temperature elevation achieved under heaters (Figure 5.6b and Table 5.5). This is explained by the higher mean wind speed occurring when crown temperature elevation levels were ≤25th percentile, relative to the remainder of times (7.7 vs. 4.5 m/s). High wind speeds would have reduced down-coming IR radiation applied by heaters via forced convection heat losses from heater elements (Kimball 2005). Subsequently, infrared heating achieved during these times may have been insufficient to elicit differences between contrasting irrigation frequency treatment levels.

Table 5.5 Elevation of irrigated perennial ryegrass crown temperatures under heaters (difference between paired heat wave and unheated reference subplots). Irrigation was applied every 2, 5, or 10 days. Analyses are presented for the 10th, 25th, 50th, 75th, and 90th percentiles. Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

Percentile	*P*-value	Irrigation frequency	Crown temperature elevation		
10th	≥0.05	2 day	**4.5**	(-0.59 ± 0.07)	
		5 day	**5.0**	(-0.61 ± 0.10)	
		10 day	**5.4**	(-0.58 ± 0.03)	
25th	≥0.05	2 day	**4.9**	(-0.42 ± 0.35)	
		5 day	**5.9**	(-0.37 ± 0.31)	
		10 day	**6.1**	(-0.32 ± 0.12)	
50th	<0.0001	2 day	**5.5**	(-0.05 ± 0.03)	C
		5 day	**6.5**	(-0.02 ± 0.04)	B
		10 day	**7.0**	(0.02 ± 0.02)	A
75th	<0.01	2 day	**6.0**	(0.33 ± 0.07)	B
		5 day	**7.6**	(0.42 ± 0.06)	A
		10 day	**7.8**	(0.43 ± 0.03)	A
90th	<0.0001	2 day	**6.1**	(0.48 ± 0.08)	B
		5 day	**8.6**	(0.64 ± 0.14)	A
		10 day	**8.4**	(0.59 ± 0.04)	A

Values followed by the same letter do not differ ($P \geq 0.05$), with letters comparing irrigation frequency treatment levels within a percentile.

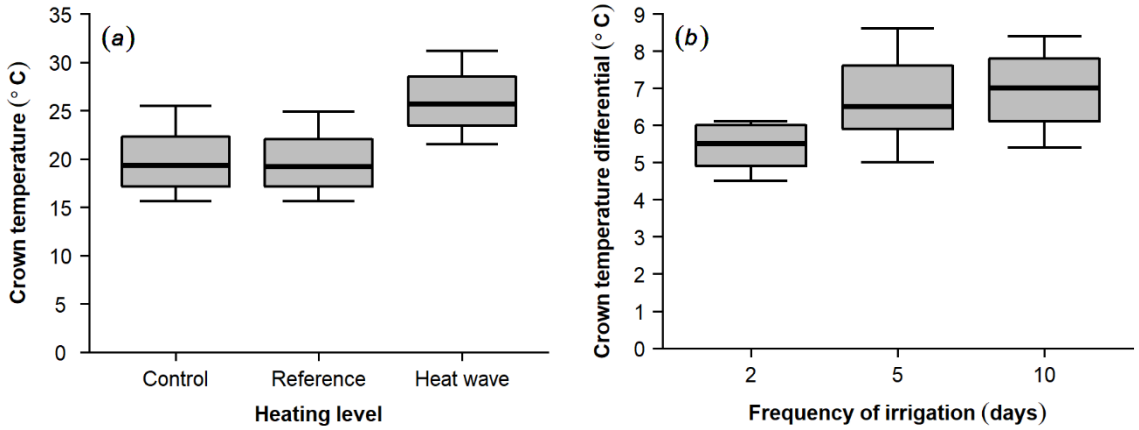

Figure 5.6 Box and whisker plots constructed from unadjusted crown temperature data. Lines represent median values (50th percentile), boxes represent the 25th and 75th percentiles, and whiskers represent the 10th and 90th percentiles. Box and whisker plot (*a)* depicts the observed effect of heating level on absolute crown temperature. The extent of crown temperature elevation (differential between paired heat wave and unheated reference subplots) under contrasting irrigation frequency treatment levels (*b*) is also presented.

We conclude that irrigating more frequently reduced the elevation of crown temperature under heaters, when conditions were conducive for IR heating (e.g. low wind speed). Although relatively small differences (Figure 5.6b), their existence suggests irrigating more frequently may benefit perennial ryegrass survival and growth during more extreme heat wave events. Explanation is partly provided by the higher vapour pressure deficits (VPD) experienced during these heat wave events. Daily VPD at key Victorian dairying regions during the January 2009 heat wave, ranged between: (i) 3.24-3.85 kPa at Ellinbank (Gippsland, south-eastern Victoria); (ii) 2.24-4.19 kPa at Warrnambool (south-western Victoria); and (iii) 2.80-5.20 kPa at Kerang (northern Victoria). Ambient daily VPD in the current study were considerably lower (H_0-H_1; μ = 0.60 kPa, range = 0.12-1.90 kPa; Table 5.3). Despite canopy level VPD being increased by IR heaters (De Boeck and Nijs 2011), it is unlikely daily VPD would have been elevated to levels experienced during the Victorian heat wave.

Higher VPD enhance plant transpirational capacity (Forde *et al.* 1977; Sermons *et al.* 2012), and subsequent ability to dissipate excess heat (Maes and Steppe 2012). This is particularly evident at high T_a temperatures, such as those experienced during heat waves (Sermons *et al.* 2012; Sermons *et al.* 2017). Realisation of higher transpirational capacities requires soil water content to be maintained at non-limiting levels, achieved by frequently irrigating to field capacity. This is particularly pertinent during heat waves akin to those experienced in Victoria, when ET rates were considerably higher than in the current study (8 vs. 3 mm/day). Higher ET rates increase depletion of soil water reserves between less frequent irrigation events (e.g. 10 day) restricting the capacity of plants to dissipate excess heat via transpiration. (Biran *et al.* 1981; Huang and Gao 1999; Richardson 2004). In the current study, soil water deficits never developed to the extent transpiration was unduly constrained. Evidence is provided by daily growth rates being unaffected by irrigation frequency (P = 0.60; Table 5.4). The limited development of soil water deficits in the current study is explained by low ET rates, and considerable rainfall during the experiment (Table 5.3).

5.7.2.2 Infrastructure

The downscaled IR heating array of Kimball *et al.* (2008) successfully maintained absolute crown temperature in heat wave subplots above their ambient counterparts (Figure 5.6a and Table 5.6). This observation was true for all examined percentiles, with one exception (10th

percentile). Heating level had no effect on absolute crown temperature at the 10th percentile (P>0.05). This contrasts previous studies, which have found IR heaters to be most effective at elevating minimum daily canopy temperatures, as they occur at night when: (i) wind speeds are low (e.g. no convective heat losses); and (ii) stomata are closed (e.g. no dissipation of applied heat via transpiration) (Van Peer *et al.* 2004; Hovenden *et al.* 2006; Kimball *et al.* 2012).

The system was programmed to elevate the T_t of the most frequently irrigated treatment level (2 day irrigation interval) by 8˚C above unheated reference plots. Direct validation of the system's capacity to maintain this level of warming cannot be made, as T_t was not logged. The system's warming capacity can be assessed from crown temperature. Overall, applied heating elevated crown temperature in the 2 day irrigated treatment by: (i) ≥4.5˚C, 90% of the time; (ii) ≥4.9˚C, 75% of the time; and (iii) ≥5.5˚C, 50% of the time (Figure 5.6b). In contrast, crown temperatures in the 10 day irrigation treatment were elevated by: (i) ≥5.4˚C, 90% of the time; (ii) ≥6.1˚C, 75% of the time; and (iii) ≥7.0˚C, 50% of the time (Figure 5.6b). Hence, the data shows increasing the heating capacity of the original IR heater array of Kimball *et al.* (2008) by reducing plot area, is an effective method of achieving significant levels of warming to simulate heat wave conditions. This suggestion is made despite elevations in crown temperature falling below the 8˚C target ΔT_t. This is because temperature elevations achieved at the crown, are expected to be significantly lower than at the tillers, due to crowns being: (i) shaded from the down-coming IR radiation applied by heaters via the canopy; and (ii) influenced by soil temperature, due to the location of the crown at the plant-soil interface. Soil, would be expected to be more resistant to temperature change than tillers, due to possessing a greater thermal mass. Soil irrigated every 2 days would have also been especially resistant to temperature changes, possessing a high thermal conductivity and volumetric heat capacity (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015). Soil evaporation may have further limited soil temperature elevations near the surface (Qiu and Ben-Asher 2010).

This study has shown the novel control system detailed in this paper can be used to quantify potential benefits of heat wave mitigation strategies. The system was successfully deployed and showed irrigating more frequently limited the elevation of crown temperatures under heaters. Subsequently, this control system provides potential for use in other similar studies.

It should also be noted, that the IR heater array infrastructure minimally affected examined variables, as determined by comparing control and unheated reference subplots (Tables 5.4 and 5.6). Infrastructure effects were only detected for the 90th percentile of absolute crown temperature (P<0.01, Table 5.6), which was higher in control relative to unheated reference subplots (25.5 vs. 24.9˚C, respectively). This difference may pertain to shading caused by the IR heating array. Shading may have sufficiently reduced incoming SR to limit crown temperature extremes (90th percentile). Despite the existence of this difference, the magnitude was relatively small, and insufficient to affect daily growth rates; neither ambient heating level affected daily growth rates (P>0.05, Table 5.4). This finding provides confidence that the deployed arrays did not cause undue artefacts. It should also be noted the shading provided by the arrays when the sun was at zenith (8%) fell below the 10% acceptable upper limit proposed by Kimball *et al.* (2012) for IR heater arrays.

Table 5.6 Absolute crown temperatures for perennial ryegrass exposed to contrasting irrigation frequency (I) and heating (HL) level treatments. Irrigation was applied every 2, 5, or 10 days. Heating levels included control (no-infrastructure), reference (non-functional infrared heater array), ambient (control and reference combined), and heat wave (functional infrared heater array). Interaction of fixed terms (FT) is omitted, due to being non-significant ($P \geq 0.05$). Analyses are presented for the 10th, 25th, 50th, 75th, and 90th percentiles (perc.). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

Analysis	FT	Percentile	*P*-value	Treatment level	Crown temperature		
Infrastructure	HL	10th	≥0.05	Control	**15.6**	(-0.78 ± 0.10)	
				Reference	**15.6**	(-0.75 ± 0.04)	
		25th	≥0.05	Control	**17.1**	(-0.39 ± 0.05)	
				Reference	**17.1**	(-0.39 ± 0.02)	
		50th	≥0.05	Control	**19.3**	(-0.07 ± 0.06)	
				Reference	**19.2**	(-0.06 ± 0.02)	
		75th	≥0.05	Control	**22.3**	(0.27 ± 0.04)	
				Reference	**22.0**	(0.26 ± 0.02)	
		90th	<0.01	Control	**25.5**	(0.70 ± 0.09)	A
				Reference	**24.9**	(0.59 ± 0.04)	B
Ambient vs heat wave	I	10th	≥0.05	2 day	**17.4**	(-0.75 ± 0.10)	
				5 day	**17.5**	(-0.75 ± 0.10)	
				10 day	**17.7**	(-0.79 ± 0.04)	
		25th	≥0.05	2 day	**18.9**	(-0.38 ± 0.06)	
				5 day	**19.3**	(-0.40 ± 0.05)	
				10 day	**19.4**	(-0.40 ± 0.02)	
		50th	≥0.05	2 day	**20.9**	(-0.06 ± 0.06)	
				5 day	**21.4**	(-0.07 ± 0.07)	
				10 day	**21.7**	(-0.06 ± 0.03)	
		75th	≥0.05	2 day	**23.5**	(0.24 ± 0.05)	
				5 day	**24.3**	(0.27 ± 0.05)	
				10 day	**24.9**	(0.26 ± 0.02)	
		90th	<0.0001	2 day	**26.1**	(0.89 ± 0.10)	B
				5 day	**27.3**	(0.99 ± 0.11)	A
				10 day	**28.1**	(1.05 ± 0.05)	A
	HL	10th	≥0.05	Ambient	**15.6**	(-0.79 ± 0.04)	
				Heat wave	**21.5**	(-0.75 ± 0.09)	
		25th	<0.0001	Ambient	**17.1**	(-0.40 ± 0.02)	B
				Heat wave	**23.4**	(-0.26 ± 0.05)	A
		50th	<0.0001	Ambient	**19.2**	(-0.06 ± 0.03)	B
				Heat wave	**25.7**	(0.19 ± 0.06)	A
		75th	<0.0001	Ambient	**22.2**	(0.26 ± 0.02)	B
				Heat wave	**28.5**	(0.54 ± 0.05)	A
		90th	<0.0001	Control	**25.5**	(0.78 ± 0.10)	B
				Reference	**24.9**	(0.67 ± 0.10)	C
				Heat wave	**31.2**	(1.05 ± 0.05)	A

Values followed by the same letter do not differ ($P \geq 0.05$), with letters comparing treatment levels within a percentile.

5.8 CONCLUSIONS/RECOMMENDATIONS

This paper concludes that freestanding IR heater arrays are a suitable system for reliably imposing heat wave conditions. Freestanding IR heater arrays have the additional advantage of incurring minimal unwanted artefacts when applied heating is regulated appropriately. This paper shows increasing the heating capacity of the original freestanding IR heater array of Kimball *et al.* (2008) by halving the array diameter, enables heat wave conditions to be imposed during average summer conditions. Despite incurring greater shading relative to the original array, the modified freestanding IR heater array imposed minimal artefacts.

The novel control system detailed in this paper was successfully used to determine irrigating more frequently reduced the elevation of perennial ryegrass crown temperature under IR heaters. This finding suggests the system is suitable for studies evaluating the ability of contrasting mitigation strategies to reduce detrimental heat wave effects on pastures.

Table 5.7 Supplementary table detailing componentry used in construction of the infrared (IR) heater array and control system. Abbreviations include: (i) alternating current, AC; (ii) direct current, DC; (iii) height, H; (iv) length, L; (v) temperature, temp; and (vi) width, W.

Item	Model	Manufacturer Name	Location	Description	Specifications/dimensions	Required quantity
1	FT-1000 (successor of FTE-1000)	Mor Electrical Heating Association Inc.	Comstock Park, MI, United States of America	Yellow-glazed, ceramic, IR heating element	• 1000 W, 240 V • 0.96 emissivity • 245 mm L x 60 mm W	6 x functional IR heater array
2	ALEX-F	Mor Electrical Heating Association Inc.	Comstock Park, MI, United States of America	Aluminium extrusion assembly housing for ceramic IR heaters	• 254 mm L x 98.6 mm W x 89.4 mm H	6 x functional IR heater array
3	Silcoset® 158	ACC Silicones Ltd.	Bridgewater, United Kingdom	High temperature resistant silicone	Operating temp. range, -60˚C to 300˚C	-
4	25980BK	Bambach Wires and Cables Pty Ltd.	Brookvale, NSW, Australia	High temperature resistant silicone rubber multi core cable	• Operating temp. range, -10˚C to 150˚C • 0.6/1 kV, 24 A • 2-core + earth	10 m x IR heater
5	Arduino® Uno REV3 microcontroller	Arduino® AG	Somerville, MA, United States of America	Microcontroller board	-	1
6	Adafruit® data logging shield for Arduino®	Adafruit® Industries	New York City, NY, United States of America	Arduino® shield with real time clock	-	1
7	Powertech® MP3490	Electrical Distribution Pty Ltd.	Silverwater, NSW, Australia	Switchmode mains adaptor	• Input: 100-240 V AC, 50/60 Hz • Output: 12 V DC, 2.5 A	1
8	DS18B20 1-wire® digital thermometers	Maxim integrated™	San Jose, CA, United States of America	Digital thermometer	• Accurate to ± 0.5˚C between -10˚C to 85˚C • 4.6 mm L x 4.6 mm W x 3.6 mm H	10
9	Clipsal® Category 5e UTP LAN Cable	Schneider Electric	Rueil-Malmaison, France	Ethernet cable	2-core	600 m
10	Ribbon cable 16 core	Jaycar Electronics	Sydney, NSW, Australia	Ribbon cable 16 core	• Rated to 105˚C • Stripped to 3-core • Per core; 1.27 mm W x 0.9 mm H	0.85 m x digital thermometer
11	WB1540	Jaycar Electronics	Sydney, NSW, Australia	Round screened cable	• 4-core • 6 mm outer diameter	0.3 m x digital thermometer
12	Loctite® SI 5145™ sealant	Henkel AG & Co., KGaA	Düsseldorf, Germany	Non-acidic silicone	Operating temp., up to 200˚C	-
13	62CEOC1KV	Prysmian Australia Pty Ltd.	Liverpool, NSW, Australia	PVC multicore circular cable	• 0.6/1kV • 2-core + earth	90 m x functional IR heater array
14	ATmega328P microcontroller	Atmel® Corporation	SJ, California, United States of America	Microcontroller	-	1

Chapter 6: **Effect of stubble height and irrigation management on the growth, botanical composition and persistence of perennial ryegrass, tall fescue, and chicory swards in cool-temperate Tasmania**

6.1 OVERVIEW OF CHAPTER 6

This thesis documents experiments investigating individual strategies for mitigating detrimental effects of hot and dry summer conditions on pasture production (Chapters 3-5). These strategies included, incorporating alternative species into the feed-base (Chapter 3), and modifying aspects of feed-base management (Chapters 4-5). To conclude the experimental section of this thesis, Chapter 6 reports a field experiment investigating the combined effect of imposed mitigation strategies on pasture production in north-west Tasmania. North-west Tasmania is identified as a region where summers are expected to become hotter challenging the perennial ryegrass (*Lolium perenne* L.)-dominated feed-base (White *et al.* 2010; Harrison *et al.* 2016; Harrison *et al.* 2017).

This experiment aimed to further explain the effects of stubble height (height of stubble above the soil surface post-defoliation) management on growth of perennial ryegrass, tall fescue (*Festuca arundinacea* Schreb.), and chicory (*Cichorium intybus* L.) swards grown under contrasting irrigation schedules or rain-fed conditions. Emphasis is given to specific management requirements needed during summer-autumn seasons. Research reported in Chapter 6 tested the hypothesis that in north-west Tasmania, tall fescue and chicory can be used to increase summer-autumn growth beyond that achievable by perennial ryegrass.

6.2 ABSTRACT

The profitability of dairying in south-eastern Australia can be improved by increasing summer-autumn pasture production, when growth rates for the existing perennial ryegrass (*Lolium perenne* L.) feed-base are low. A study undertaken in cool-temperate north-west Tasmania examined the effect of stubble height and irrigation management on perennial ryegrass, continental (summer-active) tall fescue (*Festuca arundinacea* Schreb.), and chicory (*Cichorium intybus* L.) swards. Irrigation treatments included full (~20 mm of water applied at every 20 mm precipitation deficit), deficit (~20 mm of water applied at every second full irrigation event), and nil-irrigation (rain-fed).

When repeatedly defoliated to stubble heights of 35 mm or 55 mm, all species achieved greater summer-autumn yields than when defoliated to a 115 mm stubble height, irrespective of irrigation treatment. Swards were managed under a common defoliation schedule of 9 defoliation events in 12 months. Under full irrigation, second year tall fescue achieved a 10% (0.7 t DM/ha) greater summer-autumn yield than perennial ryegrass, highlighting the potential role of tall fescue in north-west Tasmanian pastures. This was further demonstrated by the species high marginal irrigation water-use index values (1.6-2.7 t DM/ML). In contrast, summer-autumn growth achieved by chicory was less or equal to perennial ryegrass.

6.3 KEYWORDS

Basal frequency, botanical composition, defoliation severity, grazing intensity, residual height, water-use efficiency

6.4 INTRODUCTION

Grazed pasture is the cheapest feed source available for dairy cows in south-eastern (SE) Australia, hence attaining high levels of pasture production underpins dairy farm business success (Savage and Lewis 2005; Chapman *et al.* 2008a). A disadvantage of the existing perennial ryegrass (*Lolium perenne* L.) feed-base is the strong seasonality in growth and nutritive value (Jacobs *et al.* 1999; Chapman *et al.* 2008a), with up to 60% of annual herbage production occurring in spring (Nie *et al.* 2004a). In this environment, perennial pasture species with potential to increase summer-autumn growth include continental (summer-active) tall fescue ecotypes [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort; syn. *L. arundinaceum* (Schreb.) Darbysh.] (Greenwood *et al.* 2006; Tharmaraj *et al.* 2008) and chicory (*Cichorium intybus* L.) (Raeside *et al.* 2014; Pembleton 2015; Lewis *et al.* 2018). This is due to their (i) deeper-root systems (Garwood and Sinclair 1979; Ward *et al.* 2013) (ii) ability to rapidly grow after summer rainfall events (Lawson *et al.* 2007; Nie *et al.* 2008) and (iii) greater heat tolerance [see Chapter 3 and Jiang and Huang (2001b)]. Listed attributes also explain tall fescue's success outside Australia, in environments where summer conditions challenge perennial ryegrass growth and persistence; i.e. southern Missouri in the United States of America (Hamilton and Kallenbach 2013). Both tall fescue and chicory also possess key attributes underpinning perennial ryegrass's popularity (Wilkins 1991), including being perennial (Rumball 1986; Raeside *et al.* 2012b), grazeable (Raeside *et al.* 2012a; Lee *et al.* 2015a), and of high nutritional value (Chapman *et al.* 2008b; Muir *et al.* 2015).

Successfully incorporating tall fescue and chicory into the existing feed-base depends on, inter alia, their ability to grow and persist, when defoliated at intervals appropriate for perennial ryegrass swards. This is because the current feed-base is dominated by perennial ryegrass (Jacobs and Woodward 2010), and having to manage these alternative species in a separate grazing rotation would unduly complicate feed-base management (Pembleton *et al.* 2015). When managed as part of a perennial ryegrass grazing rotation, aspects of tall fescue and chicory grazing management that can be optimized include the duration and intensity of defoliation events. One measure of defoliation intensity is stubble height; i.e. height of stubble above the soil surface post-defoliation (MacDonald *et al.* 2010). This is the most widely used measure of defoliation intensity, as it is more easily estimated than other

measures such as post-defoliation canopy (herbage) biomass or leaf area index (Rawnsley *et al.* 2014).

Defining an optimum stubble height for these species is complex. Some studies have shown perennial ryegrass and tall fescue growth is greatest when defoliated to stubble heights >80 mm (Matches 1966; Garay *et al.* 1999). Others advocate defoliating to more moderate stubble heights; e.g. stubble heights within the range of 40-80 mm for perennial ryegrass (Lee *et al.* 2008), and 45-55 mm for tall fescue (Kerrisk and Thomson 1990; Burns *et al.* 2002; Brink *et al.* 2010). Studies advocating stubble heights >80 mm often defoliated plants at frequencies that prevented complete restoration of the non-structural carbohydrate (NSC) reserves used to support initial post-defoliation regrowth (e.g. every 3.5 or 10 days) (Fulkerson and Donaghy 2001; Donaghy *et al.* 2008; Lee *et al.* 2015b). Reductions in NSC reserves make plants increasingly reliant on photoassimilates produced by the remaining lamina during the initial post-defoliation period (Booysen and Nelson 1975). Defoliating grasses to low stubble heights (<40 mm) is also known to deplete plant NSC reserves, because stubble is their primary NSC storage organ (Fulkerson and Slack 1994; Donaghy *et al.* 2008). This can be particularly damaging to the persistence of grasses experiencing soil water deficit or high temperatures, since these factors exacerbate the depletion of plant NSC reserves (Waller and Sale 2001; Boschma *et al.* 2003). However, other studies have shown defoliating to low stubble heights during winter does not reduce perennial ryegrass growth or persistence (Kerrisk and Thomson 1990; Lee *et al.* 2011). Chicory growth is less affected by post-defoliation stubble height than grasses (Labreveux *et al.* 2004; Lee *et al.* 2015a), which has been attributed to chicory's NSC reserves being concentrated within the tap root (Lee *et al.* 2015b).

It is concluded that stubble height effects on the growth of species must be quantified in the target environment, and under the intended management system. Justification is provided by differences amongst abovementioned studies, and the obvious influence of defoliation frequency, climate and soil water availability. At present there is a dearth of research investigating the potential for soil water availability to modify stubble height effects on pasture growth. This paper reports on a field experiment established to determine the effect of stubble height on the growth of perennial ryegrass, tall fescue, and chicory swards maintained under contrasting irrigation schedules and rain-fed conditions. All species were managed as part of a perennial ryegrass defoliation rotation, and specific emphasis is placed

on summer-autumn yields. In addition to yield, the marginal irrigation water-use index (MIWUI) of irrigated treatments is calculated, due to the ever increasing scarcity and concomitant cost of irrigation water (Neal *et al.* 2009). Our study tested the hypothesis that in north-west (NW) Tasmania, tall fescue and chicory can be grown to increase summer-autumn growth beyond that achievable by perennial ryegrass.

6.5 MATERIALS AND METHODS

6.5.1 Site and soil description

This experiment was conducted between September 2015 and April 2017 at the Tasmanian Institute of Agriculture Dairy Research Facility (41˚08'S, 145˚77'E; 155.0 m a.m.s.l), Elliott, NW Tasmania, Australia. A cool-temperate climate characterises the location, with long-term (1975-2014) mean maximum and minimum daily ambient temperatures (T_a): (i) 20.7˚C and 11.4˚C during the warmest month (February); and (ii) 11.2˚C and 4.3˚C during the coolest month (July). During the experiment, mean monthly maximum and minimum daily T_a deviated minimally from the long-term average (Figure 6.1a). At the extremes, daily T_a ranged between 1.1˚C (24 July 2016) and 27.7˚C (10 February 2016).

Long-term mean annual rainfall is 1179 mm, with 73% falling between April and October. After abiotic treatments (irrigation and stubble height) were imposed (11 January 2016), monthly rainfall (Figure 6.1b) was: (i) close to the long-term average during summer 2016 (January and February 2016); (ii) below average between early and mid-autumn 2016 (March and April 2016); (iii) above or near average between late-autumn 2016 and mid-summer 2017 (May 2016 to January 2017), with the exception of August 2016 (52 mm below average); and (iv) well below average during late-summer 2017 (February 2017, 21 mm below average) and mid-autumn 2017 (April 2017, 53 mm below average).

The experimental site had minimal undulations, and a Ferrosol soil (Red Mesotrophic Haplic Ferrosol; Isabell 1996). Before seedbed preparation commenced, soil chemical properties and fertility (0-75 mm depth) included: pH 5.7 (1:5 w/w soil-water), electrical conductivity 0.12 dS/m, and phosphorus (P) buffering index of 713 (dimensionless). Olsen-P was 14.1 mg/kg, Colwell potassium (K) 258.5 mg/kg, and KCl-40 sulphur (S) 27.1 mg/kg.

Exchangeable cation concentrations (cmol/kg) equalled 0.19 aluminium, 12.94 calcium (Ca), 2.51 magnesium, 0.67 K, and 0.27 sodium.

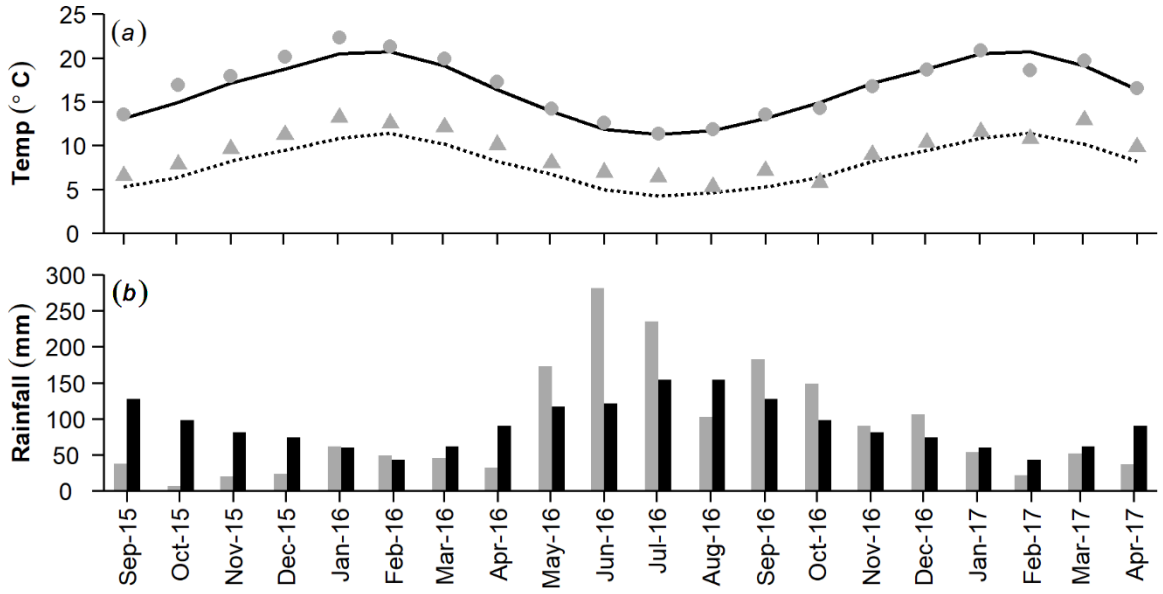

Figure 6.1 Weather data for each calendar month of the experiment (E) is presented with long-term (LT) means (1975-2014). Parameters include: (*a*) mean monthly maximum [E (●); LT (——)] and minimum [E (▲); LT (▪ ▪ ▪ ▪)] daily ambient temperatures; and (*b*) total rainfall [E (■); LT (■)].

6.5.2 Experimental design

The experiment was arranged in a split-plot design that included four replicates, which were arranged as blocks. Irrigation treatments were randomly assigned to separate main-plots within each block, and combinations of species and stubble height treatments randomly assigned to subplots within main-plots. Abiotic treatments commenced 116 days after species were sown (11 January 2016). A total of 108 subplots were included (four blocks by three irrigation treatments by three species by three stubble height treatments). Each subplot measured 2 m by 3 m and was surrounded by an 0.5 m buffer of the selected species. At minimum, 13 m separated main-plots.

6.5.3 Seedbed preparation, sowing, and establishment

On 16 July 2015, the existing perennial ryegrass pasture was sprayed out using a mixture of glyphosate [2.16 L/ha of Apparent Glyphosate 510K at 1.10 kg active ingredient (a.i.)/ha; Apparent Pty Ltd, Hawthorn East, Vic., Australia] and carfentrazone-ethyl (0.045L/ha of Hammer® at 18 g a.i./ha; FMC® Crop Protection Pty Ltd, North Ryde, NSW, Australia). Chlorpyrifos (0.9 L/ha of Apparent Dingo 500 at 0.45 kg a.i./ha; Apparent Pty Ltd) was also sprayed to suppress insect populations. On 2 August 2015, senesced herbage was grazed. The experimental site was then mouldboard ploughed to a 150 mm soil depth (19 August 2015), power harrowed (9 September 2015), and then rolled (10 September 2015). Between primary and secondary cultivation, 92.6 kg P/ha [as single superphosphate (SSP), 8.8% P, 11% S, 19% Ca] was applied to achieve an optimal Olsen-P value for perennial ryegrass growth (20 mg/kg; Cotching and Burkitt 2011). At this time, 5.3 t/ha of lime was applied to raise the soil $pH_{(water)}$ to 6.2 (Freeman 1996).

On 17 September 2015, subplots were sown with an Oyjard small-plot drill (150 mm row spacing, 10 mm sowing depth). Perennial ryegrass cv. Bealey® (NEA2, non-toxic endophyte), tall fescue cv. Quantum II® (MaxP®, non-toxic endophyte), and chicory cv. Puna® were sown at 25, 25, and 10 kg of uncoated seed/ha, respectively. Subplots were rolled immediately post-sowing, and pelletised metaldehyde baits spread around the experimental site perimeter to limit mollusc ingression (Metarex®; AgNova Technologies Pty Ltd, Box Hill, Vic., Australia). On the 3 December 2015, subplots were defoliated with a rotary lawnmower to a ~70 mm stubble height (Victa Mustang; Briggs and Stratton Corporation, Milwaukee, USA); cut material was removed, and no fertiliser applied. Between sowing and abiotic treatment imposition (17 September 2015 to 11 January 2016), 300 mm of irrigation water was applied.

On 30 October 2015, broadleaf weeds were suppressed by spraying flumetsulam (25 g/ha of Broadstrike™ at 20 g a.i./ha; Dow Agroscience Pty Ltd, Indianapolis, USA) mixed with 5 L/100 L of Uptake™ spraying oil (Dow Agroscience Pty Ltd). On 13 November 2015, chlorpyrifos (see previous rate) was sprayed to suppress *Persectania ewingii* (Westwood). On 24 December 2015, chicory subplots were re-sprayed with the flumetsulam mixture. At this time, grass subplots were sprayed with a herbicide mixture of dicamba (0.25 L/ha of Kamba® 500 at 500 g a.i./ha; Nufarm Ltd, Laverton, WA, Australia) and 2-methyl-4-chlorophenoxyacetic acid (0.8 L/ha of MCPA 750 at 750 g a.i./ha; Apparent Pty Ltd).

6.5.4 Abiotic treatments and experiment management

Irrigation and stubble height treatments commenced after a covariate harvest (H_0) on 11-12 January 2016. Irrigation treatments included two irrigation schedules (full and deficit) and nil-irrigation (rain-fed) (Figure 6.2). Full irrigation consisted of applying ~20 mm of water at every 20 mm precipitation deficit. At every second full irrigation event, ~20 mm of water was also applied on deficit irrigated main-plots; deficit irrigation is the intentional application of irrigation below evapotranspiration requirements (English 1990; Fereres and Soriano 2007). Precipitation deficits equalled the cumulative difference between reference evapotranspiration and precipitation (sum of irrigation and rainfall). Reference evapotranspiration was calculated by the FAO method (Allen *et al.* 1998) using T_a, relative humidity, solar radiation, and wind speed. Weather data were logged at 5 min intervals by an on-site automatic weather station (Vantage Pro2; Davis® Instruments Corporation, California, USA). Maximum and minimum obtainable precipitation deficits were 0 mm and 80.4 mm, respectively. The minimum precipitation deficit was determined by calculating the plant available water capacity (PAWC, mm) in the root zone, as outlined in equation 82 of Allen *et al.* (1998):

$$\mathrm{PAWC} = 1000(\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}})\mathrm{Z_r}$$

in which, θ_{FC} and θ_{WP} represent volumetric soil water content (SWC, m^3/m^3) at field capacity and wilting point, respectively, and Z_r is rooting depth (m). Volumetric PAWC differentials equalled 0.16 m^3/m^3 in the upper 0.21 m of the soil profile (0.44 m^3/m^3 – 0.28 m^3/m^3), and 0.12 m^3/m^3 in the remainder of the rooting zone (0.41 m^3/m^3 – 0.29 m^3/m^3); data sourced from previous research (pers. comm. Cotching). A maximum rooting depth of 0.6 m was assumed, based on observed SWC data (see results section).

Spray-irrigation was supplied via a pod sprinkler system (K-Line™; RXP Plastics Ltd, Ashburton, New Zealand) described by Rawnsley *et al.* (2009). Separate systems traversed the centre of each main-plot (3 m by 30 m). Each system consisted of four Naan 5035 sprinklers, fitted with 4 mm nozzles (NaanDanJain Irrigation Ltd, Na'an, Israel). Sprinklers were 10 m apart, and ≥1 m from any subplot. Irrigation water was delivered within the main-plot area at ~4 mm/h, and a distribution uniformity >80%. Irrigation water applied to full and deficit irrigation treatments totalled: (i) 177 mm and 72 mm during the first irrigation

season (January to mid-April 2016); and (ii) 281 mm and 131 mm during the second irrigation season (end of October 2016 to early-April 2017) (Figure 6.2).

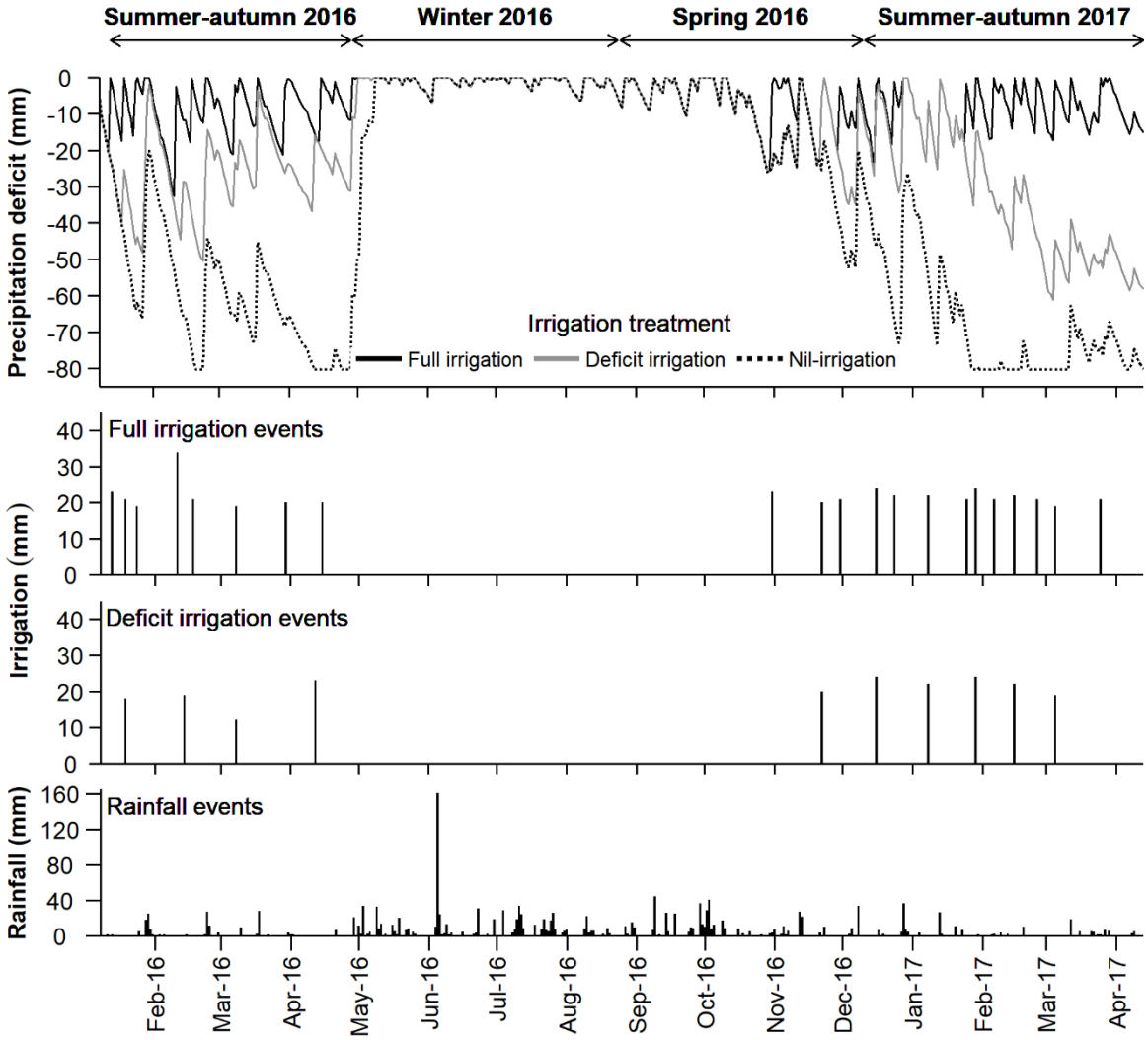

Figure 6.2 Graphical presentation at a daily resolution of calculated precipitation deficits used for irrigation scheduling. Irrigation and rainfall events are also presented.

The covariate harvest (H_0) was followed by a further twelve harvests, denoted H_1 (9-10 February 2016), H_2 (15-16 March 2016), H_3 (27-28 April 2016), H_4 (21-22 June 2016), H_5 (23-24 August 2016), H_6 (12-14 October 2016), H_7 (9-10 November 2016), H_8 (9-10 December 2016), H_9 (4-5 January 2017), H_{10} (1-2 February 2017), H_{11} (8-9 March 2017), and H_{12} (12-13 April 2017) (Figure 6.3). At each harvest, all subplots were mechanically defoliated using a rotary lawnmower (SXG326; Iseki & Co., Ltd., Tokyo, Japan). Cutting

heights were set to leave a stubble height of either 35 mm, 55 mm, or 115 mm. Scheduled harvests were based on the physiological status of the fully irrigated perennial ryegrass. Harvests generally occurred when the mean leaf regrowth stage of fully irrigated perennial ryegrass equalled 2.5 leaves/tiller. Harvests were occasionally scheduled at an earlier leaf regrowth stage (2.0 leaves/tiller) to prevent canopy closure or limit reproductive development.

Following each harvest event, 50 kg nitrogen (N)/ha (as urea, 46% N) was applied to prevent growth from becoming N limited. On 27 October 2016 and 25 November 2016, 40 kg K/ha (as muriate of potash, 50% K), 45 kg P/ha (as SSP), and 56.3 kg S/ha (as SSP) was applied. Chlorpyrifos (see previous rate) was sprayed once (15 February 2016) to suppress *P. ewingii* and *Teleogryllus commodus* (Walker) populations. No weed control was implemented after abiotic treatments were imposed.

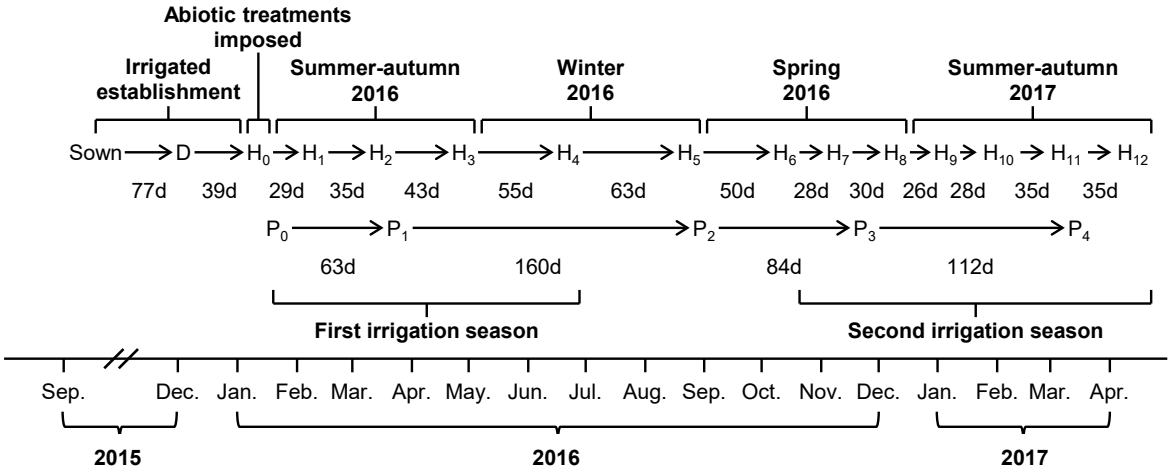

Figure 6.3 Schematic of experimental sequence. Abbreviations include: (i) defoliated, D; (ii) harvests (H), including a covariate harvest (H_0), and harvests one to twelve (H_1 to H_{12}); and (iii) GAP analysis assessments (P; e.g. persistence), including a covariate assessment (P_0), and assessments one to four (P_1 to P_4).

6.5.5 Measurements and calculations

Forty-two days after sowing (29 October 2015), seedling counts were undertaken for each species. The number of seedlings along 1 m of drill row was counted in two subplots per

main-plot. Raw seedling counts were multiplied by the number of drill rows/m (7.33) to calculate seedling density (seedlings/m^2).

Immediately before a harvest, representative hand-cut herbage subsamples (~200 g) were obtained from each subplot. Subsamples were cut to the specified stubble height for each subplot, with herbage collected along a 'W' transect. Each subsample was separated into sown and non-sown species, with the two fractions dried separately to constant weight; 60˚C for 48 h in a unithermal fan-forced drying oven (Birmingham, UK). The proportion of the sown species (botanical composition) in harvested herbage was then calculated on a dry matter (DM) basis.

At each harvest, cut herbage was removed from each subplot and weighed in the field. Dry matter content (%) of harvested herbage was calculated by drying a subsample (~200 g fresh weight) to constant weight (as previously detailed). Dry matter yield (t DM/ha) was then calculated. Harvest data were used to calculate the total DM yield achieved after abiotic treatments were imposed [sum of all harvests (H_1-H_{12})], and seasonal DM yields (sum of all harvests within a seasonal period). Seasonal periods included, summer-autumn 2016 (sum of H_1-H_3), winter 2016 (sum of H_4-H_5), spring 2016 (sum of H_6-H_8), and summer autumn 2017 (sum of H_9-H_{12}) (Figure 6.3). The MIWUI of irrigated treatments was also calculated [marginal production due to irrigation (t of DM/ha)/received irrigation (ML/ha)] for the first and second irrigation seasons, using DM yield data over the following harvests: (i) H_1-H_4 for the first irrigation season; and (ii) H_7-H_{12} for the second irrigation season.

Within a single block, volumetric SWC was monitored in each subplot defoliated to a 55 mm stubble height (i.e. monitored in 9 non-replicated subplots). Measurements were taken at 0.1 m increments, down to a 0.6 m depth, using a capacitance probe (Diviner 2000, series II; Sentek Sensor Technologies, Stepney, SA, Australia); a single access tube was present within each monitored subplot. Measurements were taken both before and ~24 hours after irrigation events, and prior to each harvest. Additional measurements were taken during the first and second irrigation seasons, which equated to a 1-3 day sampling interval. Due to a device failure, no measurements were taken between 17 January and 8 February 2017.

Sown species persistence was measured via basal frequency. Basal frequency was monitored using an adapted GAP analysis (Kemp 2011). Basal frequency was monitored in the inner six drill rows of each subplot by recording how many 50 mm increments of each drill row

contained the sown species. In each 50 mm increment, a species was deemed present if one or more tiller bases/crowns were present. An initial assessment was completed shortly after the onset of abiotic treatments (P_0, 21 January 2016), which was used as a covariate in the statistical analysis (Figure 6.3). This was followed by four further assessments, denoted P_1 (24 March 2016), P_2 (31 August 2016), P_3 (23 November 2016), and P_4 (15 March 2017).

6.5.6 Statistical analyses

Potential differences in the seedling density of each species between main-plots were assessed using a one-way analysis of variance (ANOVA). Total DM yield and MIWUI (estimated separately for each irrigation season) were analysed by split-plot ANOVA. This analytical structure was also used for seasonal DM yield within a repeated-measures context. Botanical composition and basal frequency were analysed as repeated-measures using a split-plot analysis of covariance (ANCOVA), which included the covariate (H_0 and P_0, respectively) as a continuous effect. The correlation structure of all repeated measures analyses was modelled using a one-dimensional spatial power function. This function depended on the number of days since measurements commenced for all variables, except seasonal DM yield (season replaced days). Treatment factors were assigned as stated in the *Experimental design* section. Quantile-quantile plots of residuals were generated for all variables to assess data distributions, and the presence of heteroscedasticity. Seedling density data were subsequently log transformed before analysis. Degrees of freedom were estimated using the Kenward-Roger method (Kenward and Roger 1997). Least square means were calculated, with pairwise comparisons undertaken for all significant effects. Associated *P*-values were adjusted using Tukey's adjustment for multiple comparisons. PROC MIXED and PROC PLM in SAS 9.3 (SAS for Windows Release 9.3; SAS Institute, Cary, NC, USA) were used for the analysis and post-hoc tests, respectively. Unless otherwise stated, differences discussed were significant at the $P<0.05$ level.

6.6 RESULTS

6.6.1 Soil water content

Within each irrigation treatment, changes in SWC did not substantially differ between species (Figure 6.4). Changes in SWC were concentrated within the upper 0.2 m of the soil profile.

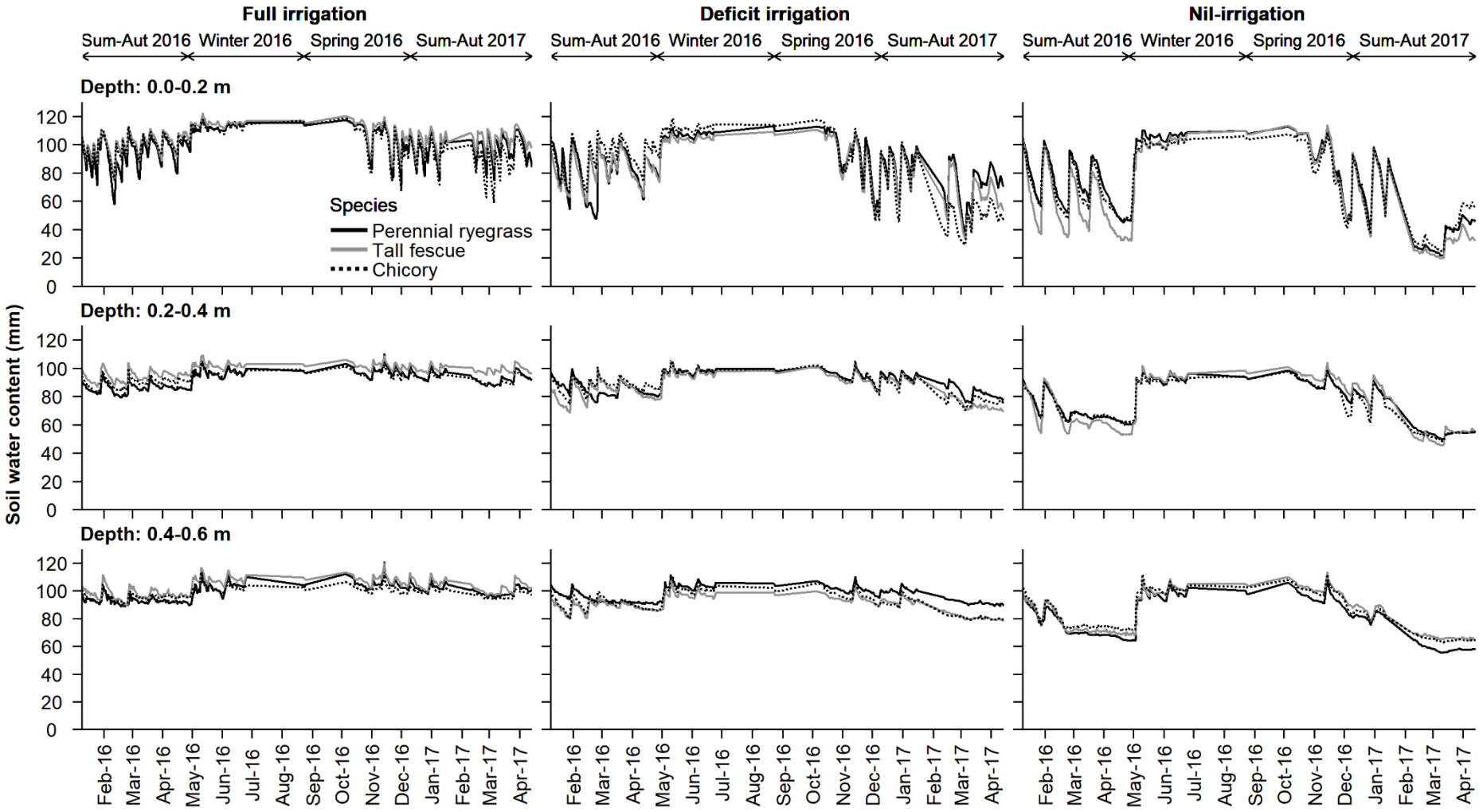

Figure 6.4 Soil water content (mm) under perennial ryegrass, tall fescue, and chicory swards. All swards were regularly defoliated to a 55 mm stubble height. Summer-autumn is abbreviated, Sum-Aut.

6.6.2 Agronomic variables

Table 6.1 shows significance levels for the main-effects and interactions included in ANOVA and ANCOVA tests for all agronomic variables but seedling density. Only the highest order significant (P<0.05) interactions for each variable are discussed.

Table 6.1 Significance levels for main-effects and interactions included in analyses of listed variables. Abbreviations include: (i) degrees of freedom, DF; (ii) dry matter, DM; (iii) irrigation treatment, I; (iv) marginal irrigation water-use index, MIWUI; (v) species, S; (vi) stubble height, SH; and (vii) time of measurement, T.

	Total DM yield		Seasonal DM yield		Botanical composition		Basal frequency		MIWUI Season 1		MIWUI Season 2	
Effect	**DF**	***P***	**DF**	***P***	**DF**	***P***	**DF**	***P***	**DF**	***P***	**DF**	***P***
Block	3 (5.9)	**	3 (5.9)	**	3 (6.7)	NS	3 (83)	**	3 (3)	NS	3 (3)	NS
Covariate					1 (155)	**	1 (83)	**				
I	2 (5.9)	**	2 (5.9)	**	2 (6.4)	NS	2 (80.3)	*	1 (3)	NS	1 (3)	*
SH	2 (71)	**	2 (72.1)	**	2 (158)	NS	2 (80.3)	NS	2 (48)	NS	2 (48)	NS
I•SH	4 (71)	NS	4 (72.1)	NS	4 (157)	NS	4 (80.3)	*	2 (48)	NS	2 (48)	NS
S	2 (71)	**	2 (72.1)	**	2 (161)	**	2 (81.4)	**	2 (48)	**	2 (48)	*
I•S	4 (71)	NS	4 (72.1)	NS	4 (157)	NS	4 (80.3)	NS	2 (48)	*	2 (48)	NS
SH•S	4 (71.4)	**	4 (72.5)	**	4 (157)	**	4 (80.3)	NS	4 (48.4)	NS	4 (48.3)	NS
I•SH•S	8 (71.3)	*	8 (72.5)	*	8 (158)	NS	8 (80.3)	NS	4 (48.4)	NS	4 (48.3)	NS
T			3 (243)	**	11 (854)	**	3 (227)	**				
I•T			6 (243)	**	22 (882)	**	6 (234)	NS				
SH•T			6 (243)	**	22 (882)	**	6 (234)	*				
I•SH•T			12 (243)	NS	44 (890)	NS	12 (238)	NS				
S•MT			6 (243)	**	22 (882)	**	6 (234)	**				
I•S•T			12 (243)	**	44 (890)	NS	12 (238)	*				
SH•S•T			12 (243)	**	44 (890)	**	12 (238)	*				
I•SH•S•T			24 (243)	NS	88 (880)	NS	24 (237)	NS				

Numerator DF are followed by denominator DF in parenthesis. P-values, NS = non-significant (P≥0.05), *P<0.05, **P<0.01.

6.6.2.1 Seedling density

Forty-two days after sowing (29 October 2015), the mean (± one standard error of the mean) seedling density of perennial ryegrass, tall fescue, and chicory equalled 401 ± 17, 537 ± 43, and 269 ± 20 plants/m^2, respectively. Within each species, seedling density did not significantly differ between main-plots.

6.6.2.2 Total DM yield

All main-effects on total yield were significant (Table 6.1), including: (i) irrigation treatment, full irrigation (22.3 t DM/ha) > deficit irrigation (20.1 t DM/ha) > nil-irrigation (16.1 t DM/ha); (ii) stubble height treatment, 35 mm (21.9 t DM/ha) > 55 mm (20.1 t DM/ha) > 115 mm (16.5 t DM/ha); and (iii) species, perennial ryegrass (21.7 t DM/ha) > tall fescue (21.0 t DM/ha) > chicory (15.7 t DM/ha). Accompanying text describes the observed three-way interaction of these main-effects on total yield (Table 6.2).

Table 6.2 Total dry matter (DM) yields (t DM/ha) achieved by three pasture species during 15 months of contrasting irrigation and stubble height (SH) management. Least-square means ± one standard error of the mean are presented; standard error of the difference ranged between 0.8-1.0.

Species	SH (mm)	Full irrigation	Deficit irrigation	Nil-irrigation
Perennial ryegrass	35	26.8 ± 0.4 Aa	25.5 ± 1.3 Aa	20.2 ± 1.0 Ab
	55	25.5 ± 0.7 ABa	23.5 ± 0.9 ABa	18.8 ± 0.5 Ab
	115	21.1 ± 1.0 CDa	19.1 ± 1.1 CDa	14.9 ± 0.6 BCb
Tall fescue	35	24.6 ± 0.9 ABa	23.7 ± 1.0 ABa	20.0 ± 0.5 Ab
	55	24.5 ± 1.6 ABCa	21.9 ± 1.2 BCa	17.5 ± 0.9 ABb
	115	22.5 ± 1.2 BCa	19.4 ± 0.9 CDa	14.9 ± 0.3 BCb
Chicory	35	22.5 ± 1.3 BCa	18.3 ± 0.9 Db	15.3 ± 1.3 BCb
	55	18.3 ± 0.7 Da	17.1 ± 1.0 Da	13.4 ± 1.1 Cb
	115	14.6 ± 0.7 Ea	12.7 ± 0.4 Eab	9.4 ± 0.6 Db

Values followed by the same: (i) uppercase letter do not differ within an irrigation treatment ($P \geq 0.05$); and (ii) lowercase letter do not differ within a row.

Within each irrigation treatment, total yields achieved by perennial ryegrass defoliated to stubble heights of 35 mm vs. 55 mm were not significantly different, but exceeded the yield achieved by the 115 mm treatment (Table 6.2). Similar stubble height effects were observed with chicory (Table 6.2). Only fully irrigated chicory contrasted this generalisation by yielding more when defoliated to a stubble height of 35 mm vs. 55 mm (22.5 vs. 18.3 t DM/ha). Stubble height did not significantly affect total yields achieved by fully irrigated tall fescue (Table 6.2). Under both deficit and nil-irrigation, total yields significantly differed between tall fescue defoliated to stubble heights of 35 mm vs. 115 mm.

At each stubble height, total yield achieved by perennial ryegrass and tall fescue under full vs. deficit irrigation were not significantly different and exceeded those attained under nil-irrigation (Table 6.2). Chicory also achieved greater total yields under full vs. nil-irrigation

(Table 6.2). Only chicory defoliated to a stubble height of 55 mm achieved significantly greater total yields under deficit vs. nil-irrigation.

Across irrigation level by stubble height treatments, total yields of perennial ryegrass and tall fescue never significantly differed from each other, although perennial ryegrass always out-yielded chicory (Table 6.2).

6.6.2.3 Seasonal DM yield

Observed effects of stubble height on the growth of species differed across seasons (Table 6.3). During summer-autumn 2016, stubble height management equally affected growth of all species, with yields ranked 35 mm > 55 mm > 115 mm. This was also true for chicory during summer-autumn 2017. During summer-autumn 2017, yields achieved by perennial ryegrass and tall fescue defoliated to stubble heights of 35 mm vs. 55 mm were not significantly different and exceeded those attained under the 115 mm treatment. Yields achieved by perennial ryegrass during winter 2016 only significantly differed between swards defoliated to stubble heights of 35 mm vs. 115 mm (3.9 vs. 3.0 t DM/ha). During spring 2016, yields achieved by chicory defoliated to stubble heights of 35 mm vs. 55 mm were not significantly different, but exceeded the yield achieved by the 115 mm treatment.

Table 6.3 Seasonal dry matter (DM) yields (t DM/ha) achieved by perennial ryegrass (PRG), tall fescue (TF), and chicory (CHIC) swards repeatedly defoliated to 35 mm, 55 mm, or 115 mm stubble heights (SH). Least-square means ± one standard error of the mean are presented; standard error of the difference equalled 0.2.

Species	SH (mm)	Summer-autumn 2016		Winter 2016		Spring 2016		Summer-autumn 2017	
PRG	35	7.7 ± 0.4	A	3.9 ± 0.1	A	6.7 ± 0.2	BC	6.0 ± 0.6	AB
	55	6.5 ± 0.3	BC	3.6 ± 0.1	AB	6.7 ± 0.1	BC	5.7 ± 0.6	BC
	115	4.3 ± 0.4	EF	3.0 ± 0.2	B	6.5 ± 0.1	C	4.5 ± 0.6	D
TF	35	6.8 ± 0.4	B	2.1 ± 0.1	C	7.2 ± 0.3	AB	6.5 ± 0.5	A
	55	6.1 ± 0.5	C	2.0 ± 0.1	C	6.9 ± 0.3	ABC	6.3 ± 0.6	AB
	115	4.5 ± 0.5	DE	2.3 ± 0.1	C	7.0 ± 0.1	ABC	5.1 ± 0.5	CD
CHIC	35	5.2 ± 0.5	D	0.4 ± 0.0	D	7.4 ± 0.2	A	5.8 ± 0.6	B
	55	3.8 ± 0.3	F	0.2 ± 0.0	D	7.5 ± 0.2	A	4.8 ± 0.4	D
	115	2.0 ± 0.3	G	0.1 ± 0.0	D	6.3 ± 0.2	C	3.8 ± 0.4	E

Within a seasonal period, values followed by the same letter do not differ ($P \geq 0.05$).

During both summer-autumn periods, yields achieved by perennial ryegrass and tall fescue were greatest under full irrigation, followed by deficit irrigation, and then nil-irrigation (Table 6.4). This was also true for chicory in summer-autumn 2017 (Table 6.4). During summer-autumn 2016, chicory achieved a greater yield under full irrigation than for either deficit or nil-irrigation, which did not significantly differ.

Table 6.4 Seasonal dry matter (DM) yields (t DM/ha) achieved by perennial ryegrass (PRG), tall fescue (TF), and chicory (CHIC) swards under full, deficit and nil-irrigation. Least-square means ± one standard error of the mean are presented; standard error of the difference ranged between 0.1-0.2.

Species	Irrigation	Summer-autumn 2016		Winter 2016		Spring 2016		Summer-autumn 2017	
PRG	Full	7.4 ± 0.5	A	3.4 ± 0.2	A	6.5 ± 0.1	C	7.2 ± 0.2	B
	Deficit	6.3 ± 0.5	B	3.5 ± 0.2	A	6.6 ± 0.2	BC	6.2 ± 0.3	C
	Nil	4.8 ± 0.4	CD	3.6 ± 0.1	A	6.7 ± 0.1	BC	2.8 ± 0.2	E
TF	Full	7.2 ± 0.4	A	2.0 ± 0.1	B	6.7 ± 0.2	BC	7.9 ± 0.2	A
	Deficit	6.1 ± 0.4	B	2.1 ± 0.1	B	6.9 ± 0.2	ABC	6.5 ± 0.3	BC
	Nil	4.1 ± 0.4	D	2.4 ± 0.1	B	7.5 ± 0.2	A	3.5 ± 0.2	E
CHIC	Full	5.0 ± 0.5	C	0.2 ± 0.0	C	7.0 ± 0.3	ABC	6.2 ± 0.3	C
	Deficit	3.3 ± 0.3	E	0.2 ± 0.0	C	7.2 ± 0.3	AB	5.2 ± 0.4	D
	Nil	2.6 ± 0.4	E	0.1 ± 0.0	C	7.0 ± 0.3	ABC	3.0 ± 0.3	E

Within a seasonal period, values followed by the same letter do not differ ($P \geq 0.05$).

Within each stubble height or irrigation treatment, perennial ryegrass yields generally equaled (summer-autumn 2016, spring 2016, summer-autumn 2017) or exceeded (winter 2016) tall fescue (Tables 6.3 and 6.4). Tall fescue attained higher yields than comparably managed perennial ryegrass when nil-irrigated during spring 2016, and fully irrigated in summer-autumn 2017.

Chicory yields were generally less than comparably managed perennial ryegrass during summer-autumn 2016, winter 2016, and summer-autumn 2017 (Tables 6.3 and 6.4). During spring 2016, yields achieved by chicory: (i) exceeded perennial ryegrass when defoliated to stubble heights of 35 mm or 55 mm; and (ii) were not significantly different to perennial ryegrass when defoliated to a stubble height of 115 mm or for any irrigation treatment.

6.6.2.4 Botanical composition

Herbage harvested from perennial ryegrass swards consistently contained a high proportion (≥80%) of the sown species (Figure 6.5). Between summer and late-spring 2016 (H_1-H_7, February-November 2016), herbage removed from tall fescue swards also contained a high proportion of the sown species (Figure 6.5). In subsequent harvests, only herbage removed from swards defoliated to a stubble height of 115 mm consistently contained a high proportion of tall fescue.

The proportion of the sown species in herbage harvested from chicory swards was variable (Figure 6.5). Across all stubble height levels the percentage of chicory in harvested herbage was >70% during summer-autumn 2016 (H_1-H_3, February-April 2016), declining to 0% by the end of winter 2016 (H_5, August 2016), and returning to ≥69% by the end of spring 2016 (H_8, December 2016). The proportion of chicory in herbage harvested from swards defoliated to stubble heights of 35 mm vs. 55 mm only differed on one occasion (H_4, June 2016), but on occasions, exceeded that attained under the 115 mm treatment.

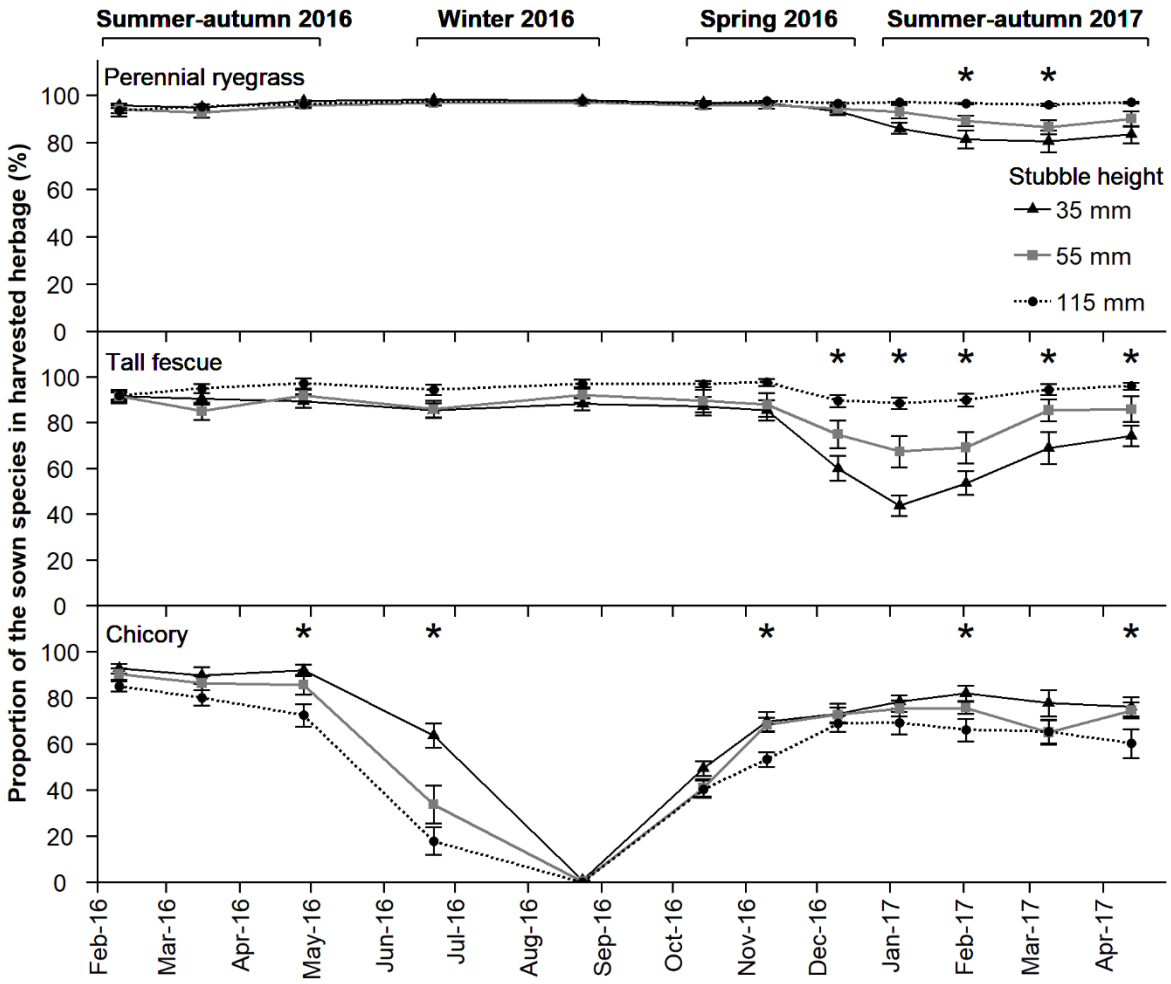

Figure 6.5 Proportion of the sown species on a dry matter basis in herbage harvested from perennial ryegrass, tall fescue, and chicory swards. Swards were repeatedly defoliated to a 35 mm, 55 mm, or 115 mm stubble height. Values are least square means ± one standard error of the mean; standard error of the difference ranged between 2.4-4.7%. Within a measurement time, an asterisk (*) indicates that a significant difference (P<0.05) existed between stubble height treatments.

6.6.2.5 Basal frequency

Variations in GAP analysis scores are explained by the interactions of: (i) irrigation treatment by species by measurement time; and (ii) stubble height treatment by species by measurement time (Table 6.1). Irrespective of irrigation or stubble height management, GAP analysis scores for perennial ryegrass remained constant (range, 233-255). With one exception similar observations were made for tall fescue. Towards the end of summer-autumn 2017 (P_4, 15 March 2017), GAP analysis scores were significantly lower for tall fescue defoliated to stubble heights of 35 mm (240) vs. 115 mm (259).

Between the end of summer-autumn and spring 2016 (P_1-P_3, March-November 2016), GAP analysis scores for chicory remained constant (range, 212-234). At P_4, GAP analysis scores for chicory were significantly lower than all prior measurements (P_1-P_3). Averaged across stubble height levels, GAP analysis scores for chicory declined by 17% between P_3 and P_4. GAP analysis scores for chicory at P_4 were 11% and 16% lower under full irrigation (167) relative to either deficit (188) or nil-irrigation (200), respectively. At P_4, GAP analysis scores for deficit and nil-irrigated chicory were not significantly different.

6.6.2.6 Marginal irrigation water-use index

In each irrigation season, stubble height did not significantly affect MIWUI (Table 6.1). In the first irrigation season, an interaction between irrigation treatment and species was observed on MIWUI (Tables 6.1 and 6.5). Under full irrigation, MIWUI values did not significantly differ between species. The MIWUI of deficit irrigated perennial ryegrass (2.2 t DM/ML) and tall fescue (2.7 t DM/ML) did not significantly differ, but exceeded the MIWUI of deficit irrigated chicory (1.0 t DM/ML). Within each species, MIWUI values attained under full vs. deficit irrigation treatments were not significantly different.

In the second irrigation season, MIWUI values were greater under deficit than full irrigation (2.4 vs. 1.5 t DM/ML). On a species basis, only the MIWUI of perennial ryegrass and chicory significantly differed (2.1 vs. 1.7 t DM/ML), with tall fescue intermediate (1.9 t DM/ML). No significant interaction between irrigation treatment and species was observed on MIWUI in the second irrigation season (Table 6.1).

Table 6.5 Marginal irrigation water-use index values (t DM/ML) for perennial ryegrass, tall fescue, and chicory under both full and deficit irrigation. Least-square means ± one standard error of the mean are presented; standard error of the difference in the first irrigation season ranged between 0.3-0.4, and equalled 0.2 in the second irrigation season.

Irrigation	Species	First irrigation season		Second irrigation season
Full	Perennial ryegrass	1.5 ± 0.1	BC	1.6 ± 0.1
	Tall fescue	1.8 ± 0.1	ABC	1.6 ± 0.1
	Chicory	1.4 ± 0.2	BC	1.3 ± 0.1
Deficit	Perennial ryegrass	2.2 ± 0.4	AB	2.7 ± 0.2
	Tall fescue	2.7 ± 0.3	A	2.2 ± 0.2
	Chicory	1.0 ± 0.3	B	2.1 ± 0.2

Within an irrigation season, values followed by the same letter do not differ ($P \geq 0.05$). Mean separation is not presented for the second irrigation season, as the interaction was not significant ($P < 0.05$).

6.7 DISCUSSION

6.7.1 Stubble height effects

In a cool-temperate climate, repeatedly defoliating swards to stubble heights of 35 mm or 55 mm cf. 115 mm increased the growth of perennial ryegrass, tall fescue, and chicory. When defoliated to stubble heights of 35 mm or 55 mm cf. 115 mm, each species usually achieved greater total yields within each irrigation treatment (Table 6.2), and always yielded more during both summer-autumn periods (Table 6.3). When winter and spring yields achieved by each of these species were affected by stubble height, swards defoliated to shorter stubble heights again achieved greater yields (Table 6.3). Observed stubble height effects on seasonal yields were independent of tested irrigation treatments (Table 6.1).

Abovementioned findings complement previous studies, which have documented the detrimental effect of leaving a high post-defoliation stubble height (>80 mm) on cumulative growing season yields achieved by both perennial ryegrass and tall fescue (Burns *et al.* 2002; Lee *et al.* 2008; Brink *et al.* 2010). Based on the research of Parsons *et al.* (1988), we consider it probable that swards defoliated to the 115 mm stubble height had the greatest proportion of older leaves, which have a lower photosynthetic capacity than younger leaves (Jewiss and Woledge 1967; Woledge 1973). Swards defoliated to high stubble heights are also known to experience a greater loss of harvestable herbage to leaf senescence (Fulkerson and Donaghy 2001). These observations help to explain the yield penalty incurred in our study from defoliating to the 115 mm stubble height. Leaving high stubble heights is additionally known to reduce canopy light interception per unit leaf area, and thus relative growth rate (Harrison *et al.* 2012b). Repeatedly defoliating grass swards to high stubble heights may also: (i) result in the accumulation of unproductive pseudostem (Garay *et al.* 1999); (ii) permanently reduce the photosynthetic capacity of emerging leaves (Woledge 1977; Woledge 1978); (iii) reduce tiller density (Lee *et al.* 2008; Kaufononga *et al.* 2017); and (iv) promote the diversion of resources to aerial tillering contributing little to herbage production or sward persistence (Korte *et al.* 1987).

Chicory swards repeatedly defoliated to the shorter stubble heights of 35 mm or 55 mm also maintained a higher proportion of chicory in harvested herbage than swards defoliated to a 115 mm stubble height (Figure 6.5). Possible explanations include the more prostrate growth habit adopted by chicory plants defoliated to the shorter stubble heights (visually observed);

this phenotypic response has been previously reported for other broad-leaf pasture species (Ryle *et al.* 1989; Stewart 1996a). A more prostrate growth habit may have assisted in suppressing the growth of non-sown species (weeds). Alternatively, defoliating to the shorter stubble heights may have differentially damaged weeds. Regardless of mechanism, this finding is of importance, as few herbicides are registered in Australia for alleviating weeds in chicory monocultures (Clark *et al.* 2013).

When repeatedly defoliated to a 35 mm stubble height, seasonal yields achieved by perennial ryegrass and tall fescue either equalled or exceeded those achieved under the 55 mm stubble height (Table 6.3). In contrast, chicory always attained higher summer-autumn yields, when defoliated to a 35 mm vs. 55 mm stubble height. Defoliating vernalised chicory swards to shorter stubble heights has been previously advocated, as this practice maximises higher nutritive value leaf and minimises lower nutritive value stem production (Matthews *et al.* 1990; Li *et al.* 1994; Lee *et al.* 2015a). Chicory was vernalised during winter 2016, as evidenced by the development of reproductive structures during spring 2016 and summer-autumn 2017 (visual observations). Achieving a target stubble height of 35 mm vs. 55 mm may be less preferable in a grazing situation, as chicory is highly sensitive to treading and pugging damage (Li *et al.* 1997; Chapman *et al.* 2012). This is because a greater number of dry sheep equivalent grazing days are required to achieve a shorter stubble height, when commencing from similar pasture covers (t DM/ha) (Harrison *et al.* 2012a). Thus, further studies should examine how chicory responds to grazing, using stubble height as a metric for comparison.

Whilst our results indicate no detrimental effects from defoliating to a stubble height of 35 mm on the productivity of examined species when defoliated at intervals appropriate for perennial ryegrass (Tables 6.2 and 6.3), the influence of environment as part of the genotype by environment by management interaction should not be ignored. While caution is required in extrapolation, we hypothesise all the species may benefit from being defoliated to higher stubble heights if exposed to warmer summer conditions. Such summer conditions are commonly experienced in other dairying regions of SE Australia (e.g. northern Victoria and southern New South Wales). This is partly because of the expected lower availability of NSC reserves in grasses defoliated to the shortest stubble heights (35 mm vs. 55 mm or 115 mm) to support elevated respiration rates during periods of supraoptimal T_a stress (Sullivan and Sprague 1949; Alberda 1965; White 1973). Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) also elevated the crown temperature of all species; see Chapter

4. As the apical meristem of these species is located at the crown during vegetative growth (Rumball 1986; Korte *et al.* 1987; Yang *et al.* 1998), high crown temperatures (≥32˚C) may have negative implications for their productivity and persistence (Peacock 1975b).

6.7.2 Irrigation effects

Marginal irrigation water-use index values for each species were often discernibly higher than the industry standard of 1 t DM/ML (Table 6.5) (Rawnsley *et al.* 2007b). The only exception occurred in the first irrigation season, when deficit irrigated chicory had a MIWUI equal to the industry standard. High MIWUI values obtained in our study can be explained by the: (i) high uniformity of applied irrigation water; (ii) strict regulation of irrigation events, which minimised water lost to the environment (e.g. surface runoff and deep percolation); and (iii) favourable environment for deficit irrigation (Rawnsley *et al.* 2009). As yield is a primary determinant of MIWUI (Rawnsley *et al.* 2009), high MIWUI values obtained in our study can also be explained by the high N rate applied and mechanical defoliation of plots (Rawnsley *et al.* 2009). Mechanical defoliation eliminates potential yield penalties incurred by grazing (Jackson and Williams 1979; Binnie and Chestnutt 1991). These yield penalties result from: (i) trampling and pugging (Brown and Evans 1973; Nie *et al.* 2001); (ii) sod pulling (Crush *et al.* 2002; Thom *et al.* 2003); and (iii) the re-grazing of plants in short succession (Fulkerson *et al.* 1994; Fulkerson and Donaghy 2001).

In the same environment as our study, Rawnsley *et al.* (2009) increased the MIWUI of perennial ryegrass by applying 8 mm (deficit irrigation) vs. 20 mm (full irrigation) of irrigation at every 20 mm precipitation deficit (1.9 vs. 1.3 t DM/ML). This response can be explained by the deficit irrigation treatment retaining the pasture in a responsive state to summer rainfall events (Rawnsley *et al.* 2009), while decreasing the amount of applied water (irrigation and rainfall) that was lost to the environment (Schneider and Howell 2000; Brown *et al.* 2004). Only in the second irrigation season of our study, were MIWUI values significantly higher under deficit vs. full irrigation (2.4 vs. 1.5 t DM/ML). This may have been partially attributed to the first irrigation season being only half the length of the second and occurring when plants were still in an establishment phase.

Irrigation treatment effects on species growth were primarily restricted to the summer-autumn periods (Table 6.4) and were independent of stubble height (Table 6.1).

Greater summer-autumn yields were achieved by perennial ryegrass and tall fescue under full irrigation, followed by deficit irrigation and then nil-irrigation. This was also true for chicory in the second, but not the first summer-autumn period. In the first summer-autumn period, chicory was unable to respond to deficit irrigation. This explains why deficit irrigated chicory achieved a lower MIWUI in the first, relative to the second irrigation season (1.0 vs. 2.1 t DM/ML) (Table 6.5). As the first summer-autumn period directly followed the establishment period, it is possible that soil water deficits experienced in the deficit irrigation treatment constrained chicory establishment. This may have impeded the ability of chicory to grow in response to deficit irrigation events.

6.7.3 Species comparisons

Tall fescue achieved similar total yields to comparably managed perennial ryegrass (Table 6.2), and when fully irrigated, 10% (0.7 t DM/ha) greater yields in the second summer-autumn period than perennial ryegrass (Table 6.4). Similar findings have been reported in northern Victoria (Greenwood *et al.* 2006). In each irrigation season of our study, MIWUI of tall fescue and perennial ryegrass were similar (Table 6.5). This finding complements research conducted by Neal *et al.* (2011) showing continental-type tall fescue grown under a range of irrigation treatments had a water-use efficiency greater or equal to perennial ryegrass. Perennial ryegrass and tall fescue also displayed similar levels of basal frequency (measured via GAP analysis), which remained unchanged during the experiment.

Chicory's basal frequency declined between the end of spring and the second summer-autumn period. The decline was anticipated, as chicory monocultures rarely persist under grazing for longer than 3 years (Lee *et al.* 2015a). When comparably managed, perennial ryegrass always achieved greater total yields than chicory (Table 6.2), and in most stubble height and irrigation treatments yielded more than chicory during both summer-autumn periods (Tables 6.3 and 6.4). Similar findings were drawn from a modelling study, which simulated perennial ryegrass and chicory growth at the experimental location (Pembleton 2015). The sensitivity of chicory growth to low temperatures explains why the percentage of chicory in harvested herbage ranged from 0% during winter to ≥60% during summer-autumn periods (Figure 6.5) (Rumball 1986).

Tall fescue and chicory were examined as potential species that could be incorporated into the current feed-base to increase summer-autumn growth. Once established, fully irrigated tall fescue could potentially be used in NW Tasmania to increase summer-autumn yields beyond those achievable by comparably managed perennial ryegrass (Table 6.4). In contrast, chicory failed to increase summer-autumn yields beyond that achievable by perennial ryegrass (Tables 6.3 and 6.4). This observation combined with chicory's marginal winter growth provides no evidence to support the inclusion of chicory into the current NW Tasmanian dairy feed-base. It should be noted that both tall fescue and chicory swards were defoliated at frequencies most suited to perennial ryegrass, and under more species-specific management they may have performed better. In addition, the genotype by environment by management interaction should be considered when extending this finding beyond the experimental region. Both tall fescue and chicory are known to be more heat tolerant than perennial ryegrass [see Chapter 3 and (Jiang and Huang 2001b)]. Ambient temperatures experienced in our study were close to the long-term average (Figure 6.1a), and were never high enough to challenge perennial ryegrass growth and persistence; i.e. they never exceeded 30˚C (Mitchell 1956; Arcioni *et al.* 1985; Neal *et al.* 2009).

6.8 CONCLUSIONS

In a cool-temperate climate, repeatedly defoliating swards to stubble heights of 35 mm or 55 mm cf. 115 mm at a common defoliation schedule of 9 defoliation events in 12 months increased perennial ryegrass, tall fescue, and chicory growth. Stubble height effects were most evident during the summer-autumn periods, and were independent of tested irrigation treatments. Future research needs to confirm these stubble management effects under grazing and any potential impacts on the nutritive value of grazed herbage, with consideration for animal intake and production required. All species usually responded positively to deficit irrigation, achieving higher MIWUI values than the industry standard of 1 t DM/ML. Results indicate fully irrigated tall fescue may potentially be used in NW Tasmania to increase summer-autumn yields beyond that achievable by comparably managed perennial ryegrass. Like perennial ryegrass: (i) tall fescue's basal frequency remained unchanged during the experiment; and (ii) tall fescue achieved high MIWUI values, which ranged between 1.6 and 2.7 t DM/ML. Results do not indicate that chicory can be grown in NW Tasmania to increase summer-autumn yields beyond that achievable by

perennial ryegrass. More species-specific management, and environments less conducive for perennial ryegrass growth and survival may challenge this finding.

Chapter 7: **General discussion**

7.1 INTRODUCTION

This thesis investigated strategies for mitigating detrimental effects of hot and dry summer conditions (i.e. supraoptimal temperature and water deficit stress) on home-grown feed production in south-eastern (SE) Australian dairying regions. Strategies included incorporating alternative species into the feed-base (Chapter 3 and 6) and modifying aspects of feed-base management (Chapters 4 to 6). Field research was conducted in north-west (NW) Tasmania, where summer conditions are forecast to become hotter and challenge the existing perennial ryegrass (*Lolium perenne* L.)-dominated feed-base by 2040 (White *et al.* 2010; Harrison *et al.* 2016; Harrison *et al.* 2017). Findings are applicable to other dairying regions of SE Australia, where hot and dry summer conditions already constrain growth of perennial ryegrass (Rawnsley *et al.* 2007a). This concluding chapter reports key findings and conclusions of research presented in this thesis and highlights subsequent research avenues.

7.2 ALTERNATIVE SPECIES

The literature review (Chapter 2) identified summer-active temperate perennial forages with potential to increase summer pasture production in SE Australian dairying regions. Identified species included prairie grass (*Bromus catharticus* Vahl.), cocksfoot (*Dactylis glomerata* L.), tall fescue (*Festuca arundinacea* Schreb.), chicory (*Cichorium intybus* L.), narrow-leaf plantain (*Plantago lanceolata* L.), lucerne (*Medicago sativa* L.), and red clover (*Trifolium pratense* L.). An advantage of these species is that they possess key attributes underpinning perennial ryegrass success in SE Australia (i.e. being perennial, grazeable, and high forage value) (Rawnsley *et al.* 2013). Knowledge of these species tolerance to supraoptimal temperature stress was either limited or anecdotal. Understanding of potential heat tolerance is required in assisting dairy farmers to select forages that mitigate detrimental effects of hot summer conditions on home-grown feed production. A glasshouse study (Chapter 3) tested the hypothesis some of these species are more tolerant of supraoptimal temperature stress [mean day/night ambient temperature (T_a) of 38/25˚C] than perennial ryegrass.

Chicory, and to a lesser extent lucerne, plantain, and tall fescue, were identified as being more tolerant than perennial ryegrass to the combined stress of supraoptimal temperature

and water deficit (Chapter 3). Tolerance to these conditions did not pertain to growth occurring when exposed to the combination of stresses, but rather was a result of the plants capacity to survive and then resume growth under more favourable conditions (i.e. when irrigated and mean day/night T_a of 23/14˚C). These findings are supported by field observations of chicory, lucerne, and tall fescue having greater capacity than perennial ryegrass to produce herbage after rainfall during hot and dry summers (Lawson *et al.* 2007; Nie *et al.* 2008; Raeside *et al.* 2014). These species have a potential niche in dairy regions of SE Australia where supraoptimal temperature stress currently constrains perennial ryegrass or is predicted to under a warming climate.

Only two species were compared to perennial ryegrass in accompanying field experiments (Chapters 4 and 6). Chicory was selected as the most tolerant of examined species to the combination of stresses (Chapter 3). Of the three species possessing intermediate tolerance (lucerne, plantain, and tall fescue), tall fescue was chosen. An advantage of tall fescue compared to lucerne, is the species similar grazing management requirements to perennial ryegrass (Gramshaw *et al.* 1993; Raeside *et al.* 2012b, 2012a). Widespread adoption of lucerne in SE Australian dairying regions is also limited by ruminant health concerns (bloat) (Wang *et al.* 2012), and lucerne's sensitivity to both aluminium toxicity (i.e. acidic soils) and waterlogging (Dear and Ewing 2008; Smith and Fennessy 2011). Tall fescue conversely presents no ruminant health concerns when endophyte-free or infected with non-toxic endophytes (Parish *et al.* 2003), and possesses greater tolerance to aforementioned abiotic stresses (Rogers and Davies 1973; Scott *et al.* 2000; Ploschuk *et al.* 2017). Tall fescue was chosen over plantain because of the limited selection of herbicides available to manage weeds in swards containing plantain (Lockley and Wu 2008; Pembleton *et al.* 2015), and plantain monocultures being highly susceptible to weed incursion (Neal *et al.* 2009).

Field research failed to support the hypothesis that chicory can be grown in NW Tasmania to increase summer-autumn growth beyond that achievable by perennial ryegrass (Chapter 6). This was evident under both irrigated and rain-fed conditions and is based on yield data collected during two summer-autumn periods. These findings challenge the value of chicory in the NW Tasmanian dairy feed-base, as chicory monocultures rarely persist under grazing for longer than 3 years (Lee *et al.* 2015a). This is confirmed by the current research, as chicory's persistence (measured via basal frequency) started declining toward the end of the experimental period (19-months post-sowing) (Chapter 6). Other barriers to chicory's successful incorporation into the NW Tasmanian feed-base include lower marginal

irrigation water-use index (MIWUI) values than those obtained for perennial ryegrass, and limited winter growth (Chapter 6). Chicory's limited winter growth is well-documented (Rumball 1986), and contributed to the low cumulative (total) yields achieved by both irrigated and rain-fed chicory. Total yields attained by chicory over the 15-month experimental period were between 16-37% less than those obtained for comparably managed perennial ryegrass. These findings indicate chicory has limited value at the present time in NW Tasmania, but this conclusion may be challenged in the future with more species-specific management and hotter summers.

In contrast to chicory, irrigated tall fescue achieved similar total yields to comparably managed perennial ryegrass, and in the second summer-autumn period post-sowing, 10% greater yields (Chapter 6). This confirms the hypothesis that tall fescue can be successfully grown in NW Tasmania to increase summer-autumn growth beyond that achievable by perennial ryegrass. Tall fescue was shown to efficiently convert applied water into grazeable herbage, attaining comparable MIWUI values to perennial ryegrass (Chapter 6). This complements research conducted by Neal *et al.* (2011), showing tall fescue grown under a range of irrigation treatments had water-use efficiency greater or equal to perennial ryegrass. Tall fescue persisted under this NW Tasmanian environment, as shown by the species stable basal frequency during the 15-month experimental period (Chapter 6). These combined findings highlight tall fescue as a valuable alternative species for irrigated dairy pastures in NW Tasmania. Including tall fescue in the feed-base will likely become increasingly important as summers become hotter (White *et al.* 2010), given this species superior tolerance to the combined stress of supraoptimal temperatures and water deficit (Chapter 3).

The reported field research (Chapter 4) showed rain-fed chicory and established tall fescue swards experienced less extreme crown (plant-soil interface) temperatures than perennial ryegrass. A feature which may contribute to their superior growth in environments with hotter summer conditions than NW Tasmania (i.e. south-western and northern Victoria) (Greenwood *et al.* 2006; Tharmaraj *et al.* 2008; Raeside *et al.* 2014). Maintaining cooler crown temperature during periods of supraoptimal temperature stress is advantageous, due to: (i) indeterminate meristematic tissues being located at the crown of chicory and tall fescue during vegetative growth phases (Rumball 1986; Korte *et al.* 1987; Yang *et al.* 1998); and (ii) potentially limiting the depletion of non-structural carbohydrate (NSC) reserves (White 1973). Whilst transpirational cooling is an important mechanism in maintaining lower plant temperatures (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004),

it is unlikely transpiration differences fully explain the cooler crown temperatures of both tall fescue and chicory relative to perennial ryegrass. This is because similar soil water extraction patterns were observed for each species (Chapter 6). It is likely the canopy base of chicory and tall fescue swards were more shaded from incoming solar radiation (SR) thereby limiting elevations in crown temperature via direct radiation heat exchange (Harrison *et al.* 2015).

7.3 MANAGEMENT

Studies described in this thesis confirm crown temperature of aforementioned species can be manipulated by both stubble height (height of stubble above the soil surface post-defoliation) and irrigation management. Research presented in Chapter 4 confirmed the hypothesis defoliating to shorter stubble heights elevates the upper distribution of perennial ryegrass, tall fescue, and chicory crown temperatures (75th and 90th percentiles). As this thesis is concerned with supraoptimal temperature stress, data exploration was restricted to the upper end of the crown temperature distribution. Once swards were established (~14 months post-sowing), defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the 90th percentile of crown temperature in summer regrowth cycles (period between successive harvests) by an average of 4.2˚C for perennial ryegrass, 3.6˚C for tall fescue, and 1.8˚C for chicory.

Observed crown temperature differences can be partly explained by the canopy base of swards being less shaded from incoming SR when defoliated to shorter stubble heights (i.e. swards having lower leaf area indices). Greater SR interception at the canopy base can elevate crown temperatures via direct radiation heat exchange (Harrison *et al.* 2015), and by reducing soil water content near the surface (Black and Aase 1988; Matthew 1992; Liu *et al.* 2011). Reductions in soil water content can make soil surrounding the crown more susceptible to temperature increases (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015), while reducing the potential for evaporative cooling (Bremer *et al.* 2001). Defoliating to shorter stubble heights can also reduce the capacity of plants to dissipate excess heat via transpiration (Harrison *et al.* 2011).

Despite experiencing higher summer crown temperatures, each species achieved greater summer-autumn yields when defoliated to shorter stubble heights (35 mm or 55 mm cf. 115

mm) (Chapter 6). This is most likely explained by the cool-temperate climate in NW Tasmania limiting the extent and/or duration of supraoptimal crown temperatures. Research presented in Chapter 4 indicates effects of defoliating to shorter stubble heights on crown temperatures are unlikely to negatively affect the growth of the investigated species in NW Tasmania while the climate remains relatively temperate. This finding may be challenged as the Tasmanian climate is predicted to become hotter (White *et al.* 2010).

Irrigation mitigated detrimental effects of supraoptimal temperature stress on growth and survival of all species examined in the glasshouse study (Chapter 3). Advantages of maintaining soil water content close to field capacity (as practiced in the reported study) for swards experiencing supraoptimal temperature stress include: (i) maintaining plants with a high capacity to dissipate excess heat via transpiration (Feldhake *et al.* 1984; Temple and Benoit 1988; Bremer *et al.* 2001; Brown *et al.* 2004); and (ii) reducing the soils susceptibility to temperature change (Ghuman and Lal 1985; Abu-Hamdeh 2003; Arkhangelskaya *et al.* 2015).

Irrigated perennial ryegrass not only grew under supraoptimal temperatures stress, but after 18 days of this treatment yielded 74% of that attained with more moderate temperatures (day/night T_a of 23/14˚C) (Chapter 3). This finding highlights the potential role of irrigation in mitigating detrimental effects of supraoptimal temperature stress on the existing perennial ryegrass dominated feed-base. As it is often impractical to irrigate on a daily basis (as practiced in the glasshouse study), research reported in Chapter 5 tested the hypothesis irrigating more frequently reduces detrimental effects of heat waves on perennial ryegrass growth and short-term persistence (measured via basal frequency). To improve on-farm applicability of research findings, this study was conducted under field conditions, necessitating the development of an outdoor warming system to reliably simulate heat wave conditions (Chapter 5). The system features a novel control system designed for evaluating heat wave mitigation options, which enables the extent of heating to be regulated, whilst applying equal levels of heat to all plots.

This outdoor warming system was successfully deployed, with results showing irrigating at higher frequencies suppressed elevation of perennial ryegrass crown temperature under heaters (Chapter 5). Applied levels of heating were considerable, with the median crown temperature differential between heated and unheated plots 5.5˚C, 6.5˚C, and 7.0˚C for swards irrigated every 2, 5, and 10 days, respectively. Despite these results, applied heating

only reduced growth rates by 13 kg DM/ha.day (23%) when heaters were operated, and had no appreciable effect on perennial ryegrass basal frequency. This result is explained by supraoptimal crown temperatures [>32˚C; (Peacock 1975b)] occurring for <10% of the time during the simulated heat wave period.

Irrigating more frequently did not mitigate detrimental effects of applied heating on perennial ryegrass growth (Chapter 5). This result is explained by the soil water deficits never developing to an extent that transpiration was unduly constrained, due to the experimental period featuring low evapotranspiration (ET) rates and frequent rain events. As NW Tasmanian summers are projected to become hotter (White *et al.* 2010), increasing the frequency of scheduled irrigation events may become an important tool for mitigating the detrimental effects of supraoptimal temperature stress on perennial ryegrass (i.e. by suppressing plant temperature). Ambient temperature increases may not only expose plants to longer durations of supraoptimal temperature stress, but increase ET rates (Allen *et al.* 1998; ACE CRC 2010). Higher ET rates result in greater soil water depletion between infrequent irrigation events (e.g. 10 days), which may restrict a plants capacity to dissipate excess heat via transpiration (Biran *et al.* 1981; Huang and Gao 1999; Richardson 2004). Therefore, frequent irrigation schedules may have a role in mitigating detrimental effects of supraoptimal temperature stress on perennial ryegrass in hotter SE Australian dairying regions.

The ability of dairy farmers to use irrigation as a tool to mitigate supraoptimal temperature stress may become challenged as competition for irrigation water increases (Neal *et al.* 2009). This trend highlights the need for irrigation strategies that improve water-use efficiency (Harrison *et al.* 2017). Deficit irrigation is a strategy of intentionally under-irrigating, which has been successfully applied in NW Tasmania to enhance water-use efficiency by maximising summer rainfall utilisation (Rawnsley *et al.* 2009). Results presented in Chapter 6 for perennial ryegrass, tall fescue, and chicory monocultures confirm the advantage of deficit irrigation as a strategy in current climatic conditions. However, deficit irrigation may become less viable as summers become hotter, as soil water deficits will restrict the capacity of plants to dissipate excess heat via transpiration (Feldhake *et al.* 1984; Temple and Benoit 1988; Brown *et al.* 2004).

7.4 CONCLUSION/FUTURE RESEARCH DIRECTIONS

This thesis identified potential strategies for mitigating detrimental effects of hot and dry summer conditions on home-grown feed production in SE Australian dairying regions. Alternative species shown to be more tolerant than perennial ryegrass of hot and dry conditions include chicory, and to a lesser extent lucerne, plantain, and tall fescue. Research presented in this thesis, highlights the potential of tall fescue to increase summer-autumn irrigated pasture production in NW Tasmania.

This thesis investigated how feed-base management strategies can be utilised to mitigate detrimental effects of supraoptimal temperature stress on pasture performance. Leaving higher post-defoliation stubble heights (115 mm) reduced crown temperature of perennial ryegrass, chicory, and tall fescue. Irrigating more frequently suppressed the elevation of perennial ryegrass crown temperature under heaters. While these practices created significant crown temperature differences they did not benefit summer growth. These practices may become advantageous as the climate warms and may already be advantageous in hotter SE Australian dairying regions. This requires confirmation, with future research also required to evaluate the potential of these management practices at a whole farm system level.

If leaving a high stubble height is found to benefit summer growth, research is required to determine the effect of incremental increases in stubble height between 55 mm and 115 mm on crown temperatures. This is because leaving a stubble height of 115 mm for a single regrowth cycle may be a viable option for minimising the exposure of swards to short durations of supraoptimal crown temperature stress (e.g. heat waves). Continuing this practice over entire multiple regrowth cycles can reduce grazeable herbage production. An objective of the proposed research should be to identify stubble heights below 115 mm that effectively suppress crown temperature, while minimising potential yield penalties.

Lastly, this thesis documents the successful development of a novel outdoor warming system suitable for studies evaluating effectiveness of contrasting strategies for mitigating the detrimental effect of heat waves (supraoptimal temperature stress) on forages. This system has widespread applicability for other research projects tackling similar issues to this thesis.

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